STRATIGRAPHY AND SEDIMENTOLOGY OF THE UPPER PAKAWAU AND LOWER WESTHAVEN GROUPS (UPPER CRETACEOUS - OLIGOCENE), NORTHWEST NELSON

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ABSTRACT

Twelve hundred metres of Pakawau Group sediments accumulated in a rapidly subsiding trough during Haumurian to early Dannevirke times, in the vicinity north-west of the Wakamarama Fault and extending from Cape Farewell to Whanganui Inlet. The upper Pakawau Group consists of the North Cape Formation (minimum of 100-250 m), the Puponga Formation (50 m) and the Farewell Formation (300-500 m). The North Cape and Farewell Formations consist of granite, volcanic, quartzarenite and schist-bearing conglomerates, subfeldsarenite to feldsarenite sandstones, minor mudstones and thin, rare coal; lithologies are interpreted as braided stream sediments. The Puponga Formation consists of sandstones, siltstones and locally coal and minor conglomerate; lithologies are interpreted as floodplain sediments deposited during an intervening quiescent interval. Locally at Kahurangi, Pakawau Group sedimentation is represented by only 15 m of Haumurian coal bearing granule conglomerate - coarse sandstone lithologies deposited in local depressions. Paleocurrent data (North Cape and Farewell Formations) indicate derivation from the granitic, sedimentary and schistose terrain to the south and east, and that conglomerate-sandstone lateral facies changes represent local tectonic control rather than proximal-distal relationships. Silcrete and soil formation, and kaolinization, accompanied tectonic quiescence and reduced sediment supply during the early Paleocene.

The Abel Head Formation and Takaka Limestone were deposited unconformably on the Pakawau Group during Arnold to Otaian times; they consist of seventy to one hundred and forty metres of marine sandstones, mudstones, minor conglomerates, greensands and micritic fine, to sparry medium-coarse, calcarenites. Marine transgression began in the southern Kahurangi vicinity with deposition of fifty metres of tidal, inner shelf and shelf sediments during the Arnold, but did not commence in the northern Cape Farewell vicinity until the Whaingaroan, when prograding beach and nearshore sedimentation extended from Cape Farewell to Kahurangi. Following progradation, during Whaingaroan-Duntroonian times, the Kahurangi vicinity subsided relatively rapidly, whilst the Te Hapu-Cape Farewell vicinity remained static. In the Kahurangi vicinity continuous shelf sedimentation is represented by sixty metres of siltstone, glauconitic and micritic fine calcarenite, and medium-coarse calcarenite; the Te Hapu-Cape Farewell vicinity is characterized by minor unconformities and relatively thin inner shelf sedimentation. Subsidence and fine calcarenite sedimentation began in the Cape Farewell vicinity during the Waitakian, whilst medium-coarse calcarenite sedimentation continued at Kahurangi. By late Waitakian times, medium-coarse calcarenite, reflecting shallow current swept shelf conditions, prevailed throughout the Kahurangi-Cape Farewell region.

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CHAPTER I

INTRODUCTION

AIMS AND SCOPE OF INVESTIGATION

The aim of this study is to describe and interpret the upper Pakawau Group, the Abel Head Formation and the Takaka Limestone (late Cretaceous-Oligocene) in the Cape Farewell-Kahurangi Point region, N.W. Nelson.

Study of the Pakawau Group was confined to the upper three hundred metres in the Whanganui Inlet vicinity, the upper six hundred metres in the Cape Farewell vicinity where the total thickness of Pakawau Group is twelve hundred metres, but included the entire Pakawau Group at Kahurangi, where it is fifteen metres thick.

Specific objectives are the determination of types and succession of non-marine and marine sedimentary environments, facies relationships and the history and general aspects of basin development based on a study of stratigraphic succession, thickness and age relationships, sedimentary structures and textures, and compositional characteristics.

GENERAL SETTING

Location

The field area extends from Cape Farewell to Kahurangi Point, N.W. Nelson (Fig. 1.1). Data from

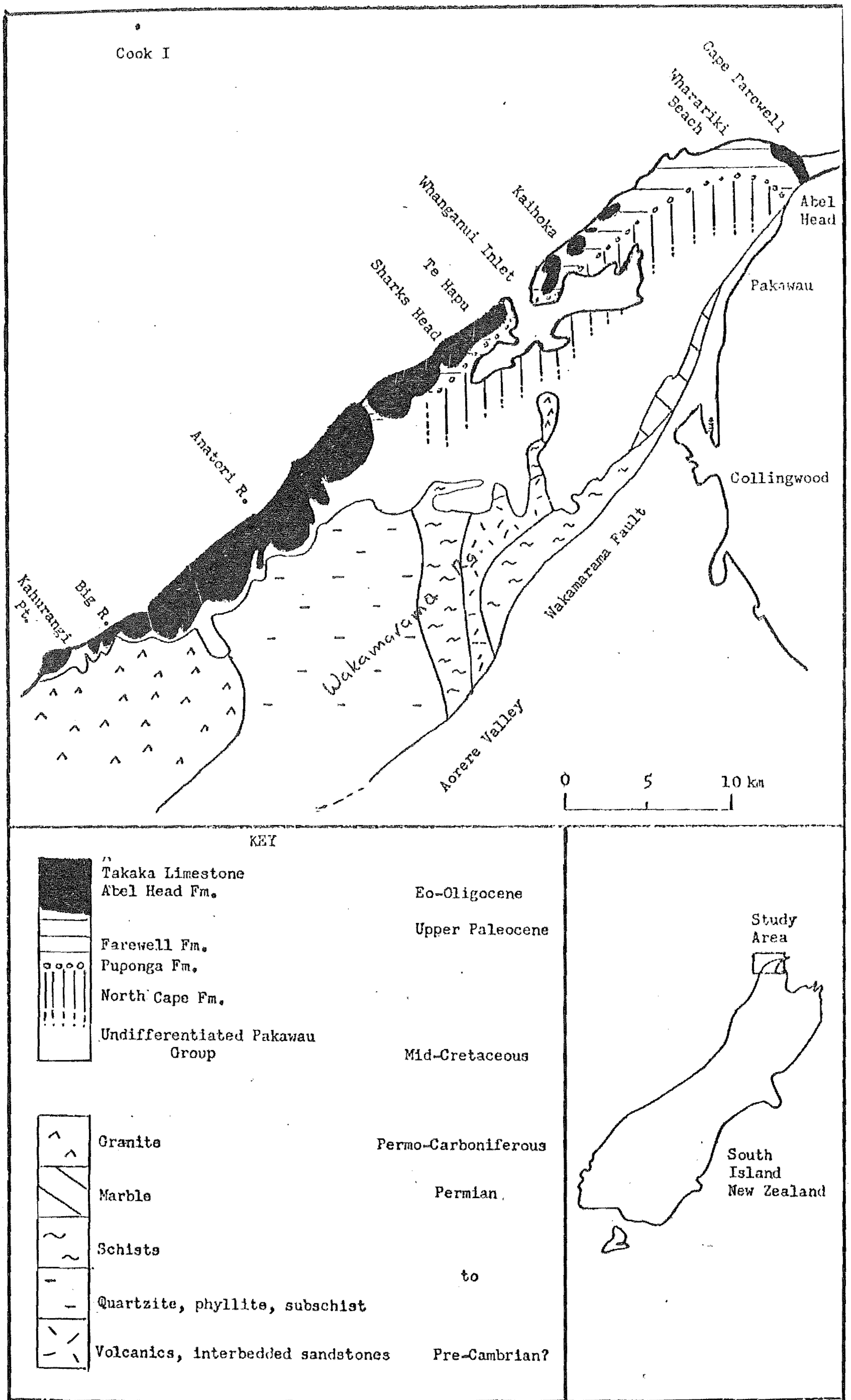


Fig. 1.1. Location and geological sketch map of study area.

fourteen sections provided basic information; data from the Cook I Well Completion Report (N.Z. Aquitane Petroleum Limited 1970) and Tertiary outliers in the Aorere Valley provided additional information incorporated in a general synthesis.

General

The coastline of steep broken cliffs, and occasional sandy beaches with a sparse or hardy vegetation, provides the best exposure of the upper Pakawau Group, Abel Head Formation and Takaka Limestone. Steep, semi-vegetated, partially cleared, pastoral and swampy low lying areas inland from the coast are poorly exposed. The steeply cliffed southern side of Whanganui Inlet entrance, and cliffed peninsulas, bays, islands and road around the Inlet provide excellent exposures of the Pakawau Group. The coastal hills and farmland merge into the Wakamarama Range (600-1300 m) where a high rainfall and humid climate support a dense podocarp-broadleaf vegetation assemblage. Despite dissection by creeks and streams exposures are poor and the area is of difficult access.

GEOLOGY

Structural setting

The structural setting is one of an elevated and tilted fault block. A basement of Paleozoic sedimentary and schistose rocks, cut by early Cretaceous granites, is unconformably overlain by mid Cretaceous-Tertiary marine and non-marine sedimentary rocks. Late Cretaceous-Tertiary sedimentary rocks (Pakawau and Westhaven Groups) are little deformed, and dip uniformly 10-15 degrees to the north-west, with the exception of Cape Farewell, where the strike is deflected by minor and localised folding. The consequence of the simple structure is a linear distribution of the thin capping of the Abel Head Formation and Takaka Limestone (70-140 m) and a broad linear distribution of the 1200 m thick Pakawau Group (see Fig. 1.1). The area is bound to the south-east by the Wakamarama Fault, which is physically expressed by the abrupt change from the low lying Aorere Valley to the rugged Wakamarama Range (Fig. 1.1).

Stratigraphic setting

A brief account of the geological history of the region is as follows (after Bishop 1971): sandstones, mudstones, volcanogenic sediments and limestones of Paleozoic age were subjected to polyphase deformation, episodes of granitic and local ultramafic intrusion, and regional metamorphism during pre-Mesozoic, Jurassic and early Cretaceous times. Relative tectonic quiescence during the early and middle Cretaceous produced a generally low lying land mass with marked local relief. Active fault movement during the early Upper Cretaceous resulted in a fault bound depression in the Cape Farewell-Kahurangi area in which twelve hundred metres of fluvial sediments accumulated during early Upper Cretaceous to early Paleocene times. During the early Paleocene, in a setting of declining tectonic tempo, fluvial sediments accumulated to the level of adjacent highs. Marine transgression began in the late Eocene, and sedimentation continued until the

Miocene. Since the Miocene the area has been uplifted by reverse movement on the Wakamarama Fault and tilted westwards.

METHODS

The following field data was recorded at select sections: thickness (determined by pacing, tape measurement, estimation from photographs), nature of contacts, grain size and sorting (estimated with grain size comparator and hand lens), composition and sedimentary and biogenic structures. Each lithotype was sampled for further laboratory investigation. Samples at selected horizons were obtained for foraminiferal and palynological analysis. Paleocurrent data was recorded when feasible.

Laboratory work consisted of thin section analysis of each distinctive rock type, extraction of foraminifera for dating purposes, and X-ray identification for confirmation of mineralogies.

CHAPTER II

STRATIGRAPHY

PREVIOUS WORK, PROPOSALS FOR REVISION OF NOMENCLATURE

Figure 2.1 reviews developments in stratigraphic nomenclature from Hutton (1885) to Bishop (1971). The recent stratigraphic subdivisions of the Pakawau Group (Suggate 1956) and Westhaven Group (Bishop 1971) have in general been based on local sections, and are not sufficiently refined for the requirements of this study. Accordingly, the existing Pakawau Group nomenclature is modified, and distribution of previously distinguished formations extended (Fig. 2.2). The Abel Head Formation and Takaka Limestone of the Westhaven Group of Bishop (1971) are divided into eight members (Fig. 2.2). Definitive features of formations and members are outlined, and a full description of characteristics is contained in subsequent sections on structure and texture, and composition. Logs of type, reference and other sections are contained in the back pocket. Figures 2.3 and 2.4 illustrate time and areal distribution and thickness variation at three principal sections of Pakawau Group Formations, the Abel Head Formation and the Takaka Limestone.

Upper Pakawau Group

The non-marine upper Pakawau Group exhibits a coarse-fine-coarse vertical sequence characterized by sandstones, granule and minor pebble-cobble conglomerate, fine sandstones and siltstones, and coarse sandstones in the Whanganui Inlet vicinity.

The Abel Head vicinity exhibits a comparable coarse-fine-coarse sequence, characterized by conglomerate, siltstone and coal, and conglomerate (Fig. 2.2) that is of similar age to the Whanganui Inlet sequence. Suggate (1956) divided the Cape Farewell sequence into the North Cape, Puponga, Wharariki and Farewell Formations (Fig. 2.1). The upper conglomeratic part of the sequence was arbitrarily divided into the Farewell and Wharariki Formations on the basis of a higher incidence of pebbly sandstones in the Wharariki Formation; a similar distinction cannot be made in the upper coarse sequence at Whanganui Inlet. The North Cape and Farewell Formations of Suggate (1956) were based on drill hole data from the Abel Head vicinity.

It is proposed to retain the names North Cape and Puponga Formations, amalgamate the Farewell and Wharariki Formations of Suggate (1956) as the Farewell Formation, and adopt the Whanganui Inlet section as the type section for the North Cape, Puponga and Farewell Formations. The Abel Head sections are retained as reference sections.

Prior to Suggate (1956), Ongley and MacPherson (1923) divided the late Cretaceous - early Tertiary lithologies into the Pakawau Series (Puponga and North Cape Formations) and the West Haven Series (Farewell Formation and Westhaven Group) (see Fig. 2.1). The division was based on a supposed break in sedimentation at the top of the Puponga Formation and supposed overlap of the West Haven Series on to Paleozoic basement in the Kahurangi vicinity. Suggate (1956) argued that the Westhaven-Pakawau Series contact was conformable because the contact at Cape Farewell was indistinct, and lithologies of the Westhaven Series (Kahurangi) and Pakawau Series (Cape Farewell) are of similar age. Suggate accordingly amalgamated the Pakawau Series and the basal non-marine part of the Westhaven Series as the Pakawau Group, and renamed the marine part of the Westhaven Series as the Westhaven Formation.

Bishop (1968, 1971) retained only the Puponga Formation of Suggate (1956), distinguished the Otimataura Conglomerate as a local formation (in the eastern Wakamarama Range), and classified the remaining bulk of the Pakawau Group as "Undifferentiated" (Fig. 2.1).

Westhaven Group

Bishop (1968, 1971) renamed the marine lithologies of the Westhaven Formation (Suggate 1956) as the Westhaven Group and divided it into the Abel Head Formation, the Takaka Limestone and the Kaipuke Siltstone (Fig. 2.1). The marine Westhaven Group rests paraconformably on the non-marine upper Pakawau Group; previously the contact has been described as conformable (Ongley and MacPherson 1923, Suggate 1956, Bishop 1971).

This study indicates that the Abel Head Formation contains a wider variety of lithotypes than the type section at Abel Head, described by Bishop (1971). The most complete and representative sections occur at Kahurangi and Te Hapu.

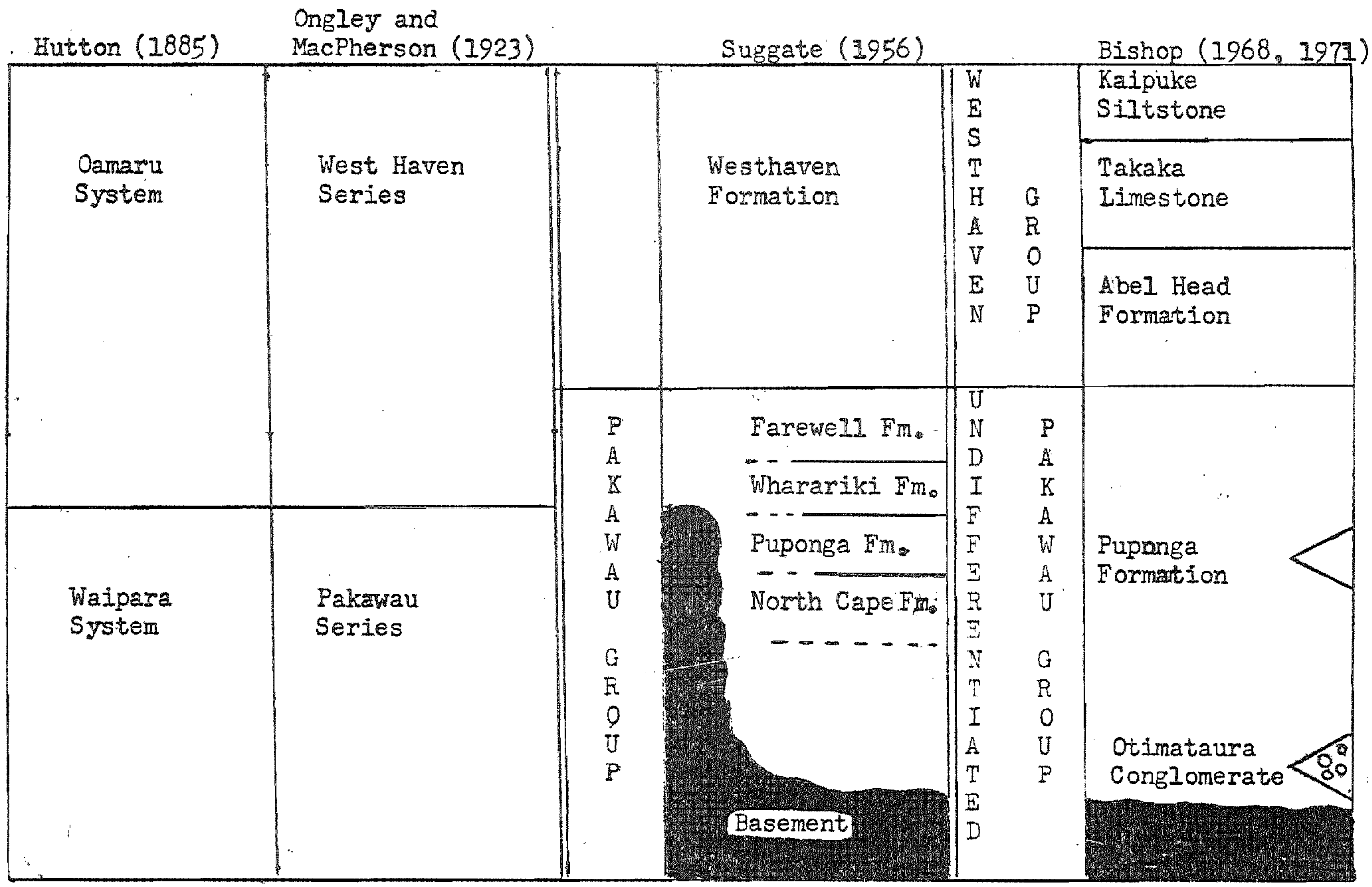


Fig. 2.1. Stratigraphic Terminology (1885-1971) of lithologies in Kahurangi-Cape Farewell vicinity.

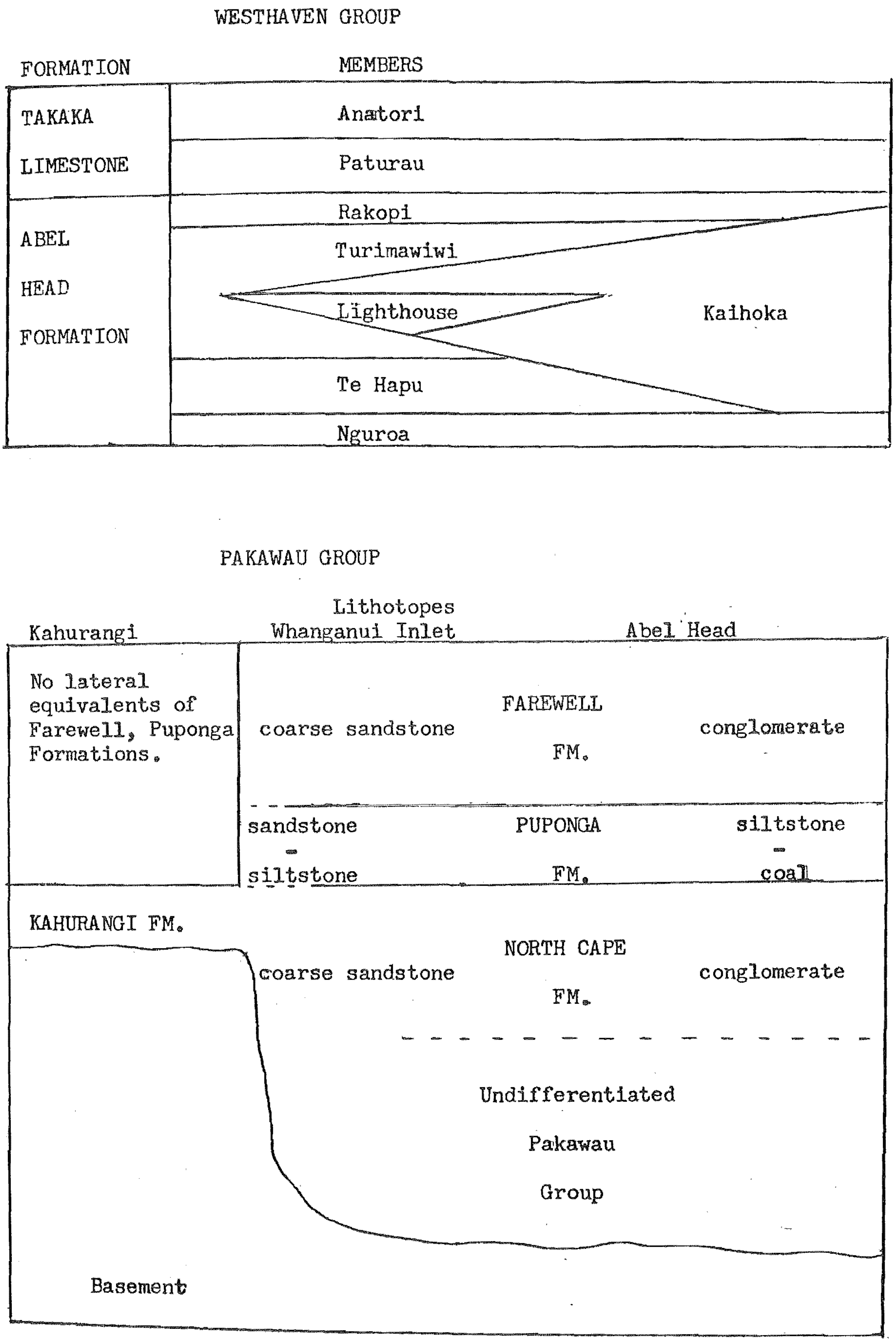


Fig. 2.2. Stratigraphic Nomenclature of Pakawau Group, Abel Head Formation and Takaka Limestone.

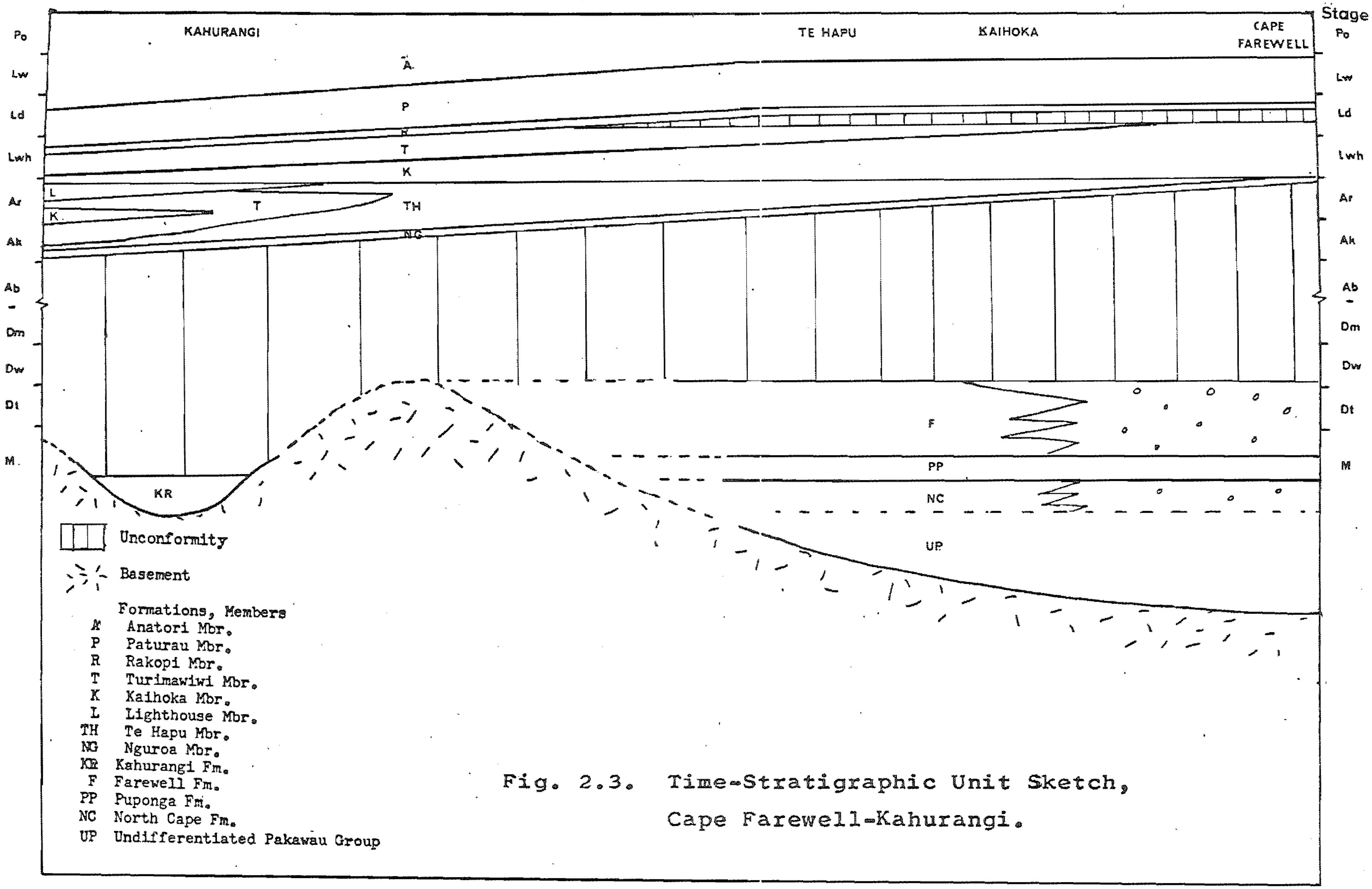


Fig. 2.3. Time-Stratigraphic Unit Sketch, Cape Farewell-Kahurangi.

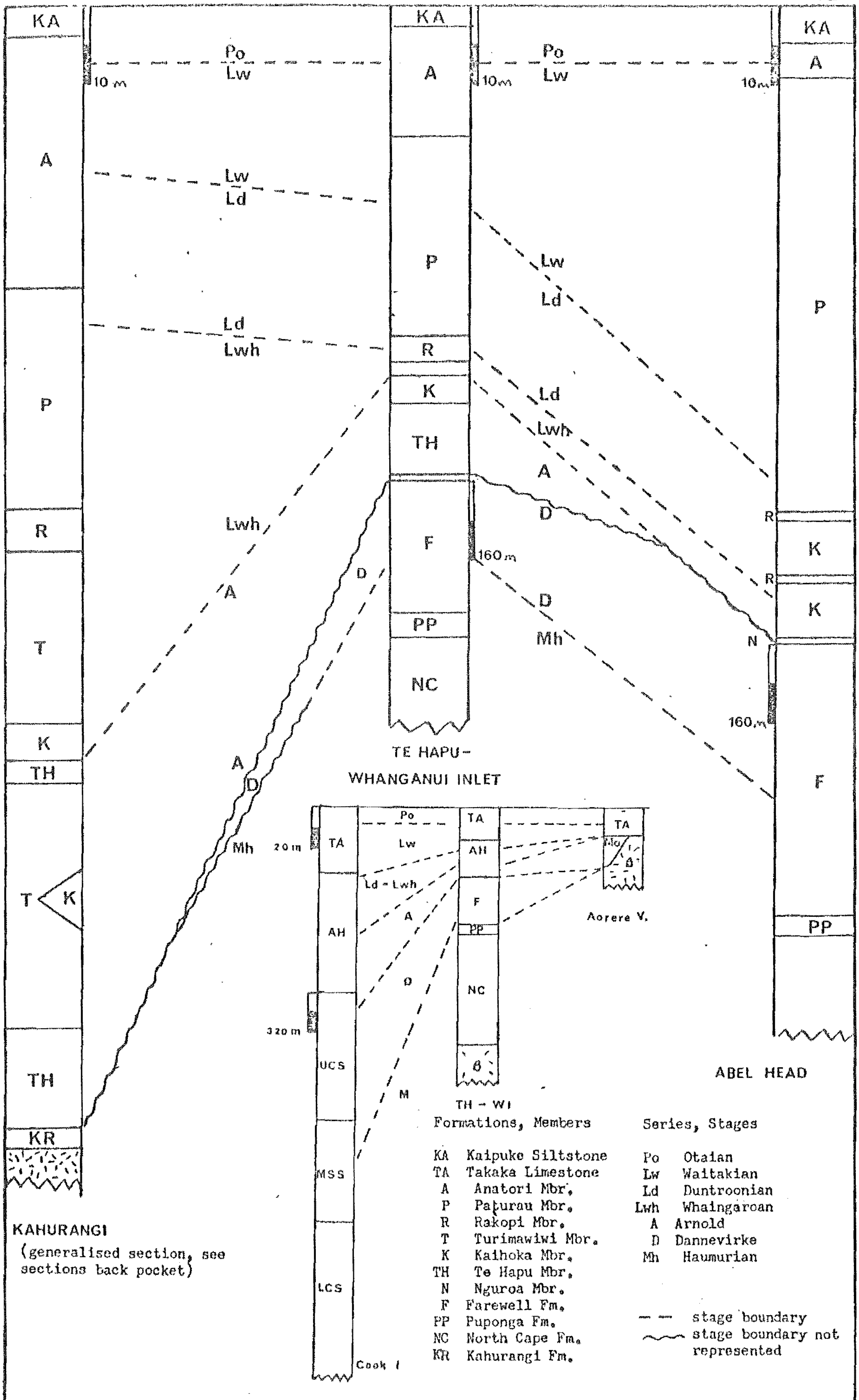


Fig. 2.4. Correlation of Kahurangi, Te Hapu-Whanganui Inlet and Abel Head Sections.

These sections contain the type and reference sections (this work) for members of the Abel Head Formation outlined in Fig. 2.2.

The upper part of the Abel Head Formation has been previously described as a calcareous siltstone or fine sandstone (Wellman, Beck *et al.* 1973, Bishop 1971). This study reveals it is a fine calcarenite (see Composition). It is proposed therefore that this unit be included in the Takaka Limestone which now consists of two members - the massive fine calcarenite Paturau Member previously described as a calcareous siltstone, and the Anatori Member formerly the Takaka Limestone of Bishop (1971).

PAKAWAU GROUP

The name Pakawau Group was proposed by Suggate (1956) for 700 metres of conglomerates, sandstones, mudstones and coal seams outcropping and recorded in drill logs in the Puponga vicinity. Bishop (1971) adopted the name for 1200 metres of similar lithologies, including those described by Suggate (1956), extending from Cape Farewell to Kahurangi Point and the Wakamarama Range (Fig. 1.1).

NORTH CAPE FORMATION

Name, Description, Type Section, Distribution

The name North Cape Formation is proposed for one hundred metres of predominantly medium sandstone to granule conglomerate, minor fine sandstones, mudstones and thin coal seams outcropping at Whanganui Inlet (see Fig. 5.4, Structures and Texture, Composition). The type section extends from the inner part of the Whanganui Inlet entrance (M25 710683) to the southern part of Whanganui Inlet (M25 685652) and the Knuckle Hill road section (M25 716650). The name North Cape Formation was originally proposed by Suggate (1956) for 250 metres of conglomerates, sandstones and impersistent coal seams recorded in drill holes in the Puponga vicinity. Drill hole S1/d8 (Suggate 1956) is designated as a reference section.

Relation to Underlying Units, Age, Interpretation

The base of the North Cape Formation was not established in the Puponga vicinity (Suggate 1956) or in the Whanganui Inlet vicinity (this study). The North Cape Formation is underlain by a maximum of 900 m of Pakawau Group lithologies ("Undifferentiated Pakawau Group" of Bishop 1971).

Microfloral samples (S1/514, S1/515) indicate a Haumurian age.

North Cape Formation lithologies are interpreted as braided stream sediments (see Interpretation).

PUPONGA FORMATION

Name, Description, Type Section, Distribution

The name Puponga Formation is proposed for fifty metres of alternating fine to medium sandstones and siltstones (see Fig. 5.7, Structures and Textures, Composition) outcropping in steep cliffs one kilometre from the entrance of Whanganui Inlet (Type Section

M25 707685). The name Puponga Formation was originally proposed by Suggate (1956) for sixty metres of sandstones, siltstones, coal seams and minor conglomerate recorded in drill logs in the Puponga vicinity. Drill hole S1/d3 (Suggate 1956) is designated as a reference section.

Relation to Underlying Units, Age, Interpretation

At Whanganui Inlet the contact with the North Cape Formation is gradational; the basal contact is arbitrarily placed 50 m below the top of the Puponga Formation.

Microfloral samples (M25/510, S1/512) indicate a Haumurian age.

The change in sediment character is interpreted as representing a transition from braided stream to floodplain sedimentation (see Interpretation).

FAREWELL FORMATION

Name, Description, Type Section, Distribution

The name Farewell Formation is proposed for 400 metres of predominantly coarse sandstone to granule conglomerate and minor fine sandstones and siltstones (see Fig. 5.5, Structures and Textures, Composition), outcropping in steep cliffs and immediately to the south of the southern side of the Whanganui Inlet entrance (Type Section M25 705693 to M25 707685). The name Farewell Formation was originally proposed by Suggate (1956) for 200 metres of conglomerate, sandstones and mudstones exposed in the cliffs in the vicinity of Cape Farewell (see Fig. 5.6, section back pocket). The Farewell Formation is extended to include 500 metres of the conglomeratic Wharariki Formation of Suggate (1956) (see Fig. 5.7, section back pocket).

Relation to Underlying Units, Age, Interpretation

In the Abel Head vicinity, drilling records (Suggate 1956) indicate a rapid transition (over several metres) or sharp contact with the underlying Puponga Formation; the contact at Whanganui Inlet is sharp and erosive.

The Farewell Formation ranges from Haumurian to lower Dannevirke in age. A microfloral sample from the top of the Farewell Formation, Whanganui Inlet (M25/f4), indicates a Teurian-Waipawan age; samples within and near the base of the formation (S1/512, S1/513) indicate a Haumurian age.

The rapid transition or sharp contact appears to record the progradation of braided stream deposits into areas of floodplain sedimentation (see Interpretation, Synthesis).

KAHURANGI FORMATION

Name, Description, Type Section, Distribution

The name Kahurangi Formation is proposed for 15 metres of coal bearing, coarse sandstone to fine pebble conglomerate lithologies outcropping at Big River (Type Section L25 476483), and an estimated minimum 10 metres of similar lithologies outcropping in sandhills south of Kahurangi Point (Reference Section L25 453483, see Fig. 5.8, Kahurangi Section back pocket).

Relation to Underlying Units, Age, Interpretation

The Kahurangi Formation nonconformably overlies a leached granite basement (Big River Section).

Microfloral sample (S2/511) indicates a Haumurian age.

The Kahurangi Formation is interpreted as representing locally derived coarse fluvial sediments and peat accumulating in local topographic depressions (see Interpretation).

WESTHAVEN GROUP

The name Westhaven Group was proposed by Bishop (1971) for marine sandstones, greensands, calcareous siltstones, limestones and local non-marine quartzose sandstones in the Golden Bay area. The Motupipi Coal Measures and Tarakohe Mudstone outcropping in the Aorere Valley, and the Kaipuke Siltstone overlying the Takaka Limestone (Kahurangi-Kaihoka) are beyond the domain of this study.

ABEL HEAD FORMATION

The name Abel Head Formation was proposed by Bishop (1971) for rusty limonitic quartzose sandstone and conglomerate, quartz grit, greensand and calcareous siltstones overlying the Pakawau Group. Apart from incorporation of the 'calcareous siltstones' in the Takaka Limestone (see proposals for revision), the existing nomenclature is retained and the formation divided into six members.

NGUROA MEMBER

Name, Description, Type Section, Distribution

The name Nguroa Members is proposed for a one metre packed pebble-cobble, quartzarenite and quartz vein - pebble conglomerate outcropping at Abel Head (Type Section M24 877764). It it distinct from underlying Farewell Formation conglomerates where gravel clasts are sand supported and include granite (see Structure and Texture, Composition). At Cape Farewell gravel components are up to boulder size; at Te Hapu the Nguroa Member ranges from sandy pebble conglomerate to pebbly coarse sandstone; at Kahurangi it is present as sparsely dispersed cobbles at the base of the Te Hapu Member.

Relation to Underlying Units, Age, Interpretation

The Nguroa Member paraconformably overlies the Pakawau Group.

The Nguroa Member is assumed to have a similar age to the immediately overlying Te Hapu or Kaihoka Members. At Te Hapu and Kahurangi the overlying Te Hapu Member is of Arnold age (M25f/5, L25f/1); the underlying Pakawau Group at the respective sections is of Teurian-Waipawan (M25f/4) or Haumurian (S2/511) age. All, or part of the Dannevirke Series is absent.

The Nguroa Member is interpreted as a residual quartzose lag produced by marine reworking of the top of the Pakawau Group during transgression (see Interpretation).

TE HAPU MEMBER

Name, Description, Type Section, Distribution

The name Te Hapu Member, is proposed for 8 metres of interbedded mudstones, mud laminated fine sandstones with slight to intense bioturbation, and minor stratified or massive coarse sandstones (see Fig. 5.9), outcropping at Te Hapu (Type Section M25 696683). At Kaihoka and Anatori, massive irregular pebble conglomerates up to 50 cm thick are also present; at Kahurangi massive and bioturbate muddy fine sandstone and fine sandy mudstone lithologies predominate. The Te Hapu Member is restricted to south of the Kaihoka Section; it is not present at Abel Head (see Fig. 2.3).

Relation to Underlying Units, Age, Interpretation

Generally the Te Hapu Member conformably overlies the Nguroa Member; locally at Kahurangi it nonconformably rests on leached granite basement.

The Te Hapu Member is of Arnold age (L25f/1, M25f/4, UC7968), and is interpreted as representing tidal deposition (see Interpretation).

KAIHOKA MEMBER

Name, Description, Type Section, Distribution

The name Kaihoka Member, is proposed for 4 metres of interbedded horizontal and cross stratified, locally micaceous, fine sandstones, massive granular very coarse to coarse sandstones and fine pebble to silty, sandy fine pebble conglomerate (see Fig.5.10), outcropping in the

Kahurangi vicinity (Type Section L25 437483). At the Te Hapu and Abel Head Sections (Fig. 5.8), and south of Kahurangi Point (Section back pocket), the Kaihoka Member is represented almost entirely by massive bioturbate granular very coarse to coarse sandstone lithologies. The Kaihoka Member extends from Cape Farewell to Kahurangi.

Relation to Other Units, Age, Interpretation

The Kaihoka Member forms sharp or gradational contacts with all other Members of the Abel Head Formation (see Figs 2.2, 2.3). The Kaihoka Member sharply overlies the Nguroa Member (Abel Head Section), the Te Hapu Member (the Te Hapu and Big River-Alva Creek Section, Kahurangi) and the Lighthouse Member (south of Kahurangi Point). Locally the Lighthouse Member is interbedded with the Kaihoka Member (Big River-Alva Creek Section, Kahurangi). The Kaihoka Member overlies and forms gradational contacts with the Rakopi Member (uppermost occurrence Abel Head Section) and the Turimawiwi Member (lowermost occurrence south of Kahurangi Point).

The age of the Kaihoka Member has not been determined; ages of underlying, overlying and interbedded Members suggest an Arnold to Whaingaroan age at Kahurangi, and Whaingaroan to Duntroonian age at Abel Head.

Kaihoka Member lithologies are interpreted as prograding beach and nearshore sediments formed in response to prograding fluvial sedimentation (Lighthouse Member, see Interpretation).

LIGHTHOUSE MEMBER

The name Lighthouse Member, is proposed for an eight metre lens of horizontally, planar and channel fill cross stratified, granular very coarse to coarse sandstones with coal fragments and perigenic siltstone clasts outcropping south of Kahurangi Point (Type Section L25 437475). Contact with the underlying Turimawiwi Member, although determinable to within several metres, is obscured by vegetation and soil cover. South of Big River (Reference Section L25 453843), it outcrops as a two metre thick channel structure, cutting into and interbedded with the Kaihoka Member (Fig. 5.10). An Arnold-Whaingaroan age is adopted. The Lighthouse Member represents a brief progradational fluvial episode (see Interpretation and Synthesis).

TURIMAWIWI MEMBER

Name, Description, Type Section, Distribution

The name Turimawiwi Member, is proposed for 30 metres of massive, bioturbate, grey calcareous siltstone outcropping between Big River and Alva Creek (Type Section L25 453483). At the base of the type section, the Te Hapu Section, and lower in the succession south of Kahurangi Point, thin lenses of coarse sandstone to fine pebble conglomerate or disseminated coarse sands occur. The member is restricted to sections south of Te Hapu (Fig. 2.3).

Relation to Underlying Units, Age, Interpretation

The Turimawiwi Member overlies the Kaihoka Member; a gradational contact over less than a metre is characterised by coarse sandy siltstone.

The Turimawiwi Member ranges from Arnold to Whaingaroan-Duntroonian age in the Kahurangi vicinity (UC7968, UC7973), and is of Whaingaroan age in the Te Hapu vicinity (UC7939).

Calcareous siltstone lithologies are interpreted as shelf deposits, coarse sandy siltstones as inner shelf to nearshore deposits (see Interpretation).

RAKOPI MEMBER

Name, Description, Type Section, Distribution

The name Rakopi Member, is proposed for micritic clayey and silty lithologies of the Abel Head Formation with greater than an arbitrary 20% glauconite. The type section is located in coastal bluffs at Te Hapu (M25 696683). Five metres of massive bioturbate lithologies at the type section contain 20-60% glauconite, and range from coarse sandy and silty glauconitic foraminiferal biomicrites to micritic glaucarenites (see Composition). The Rakopi Member extends from Cape Farewell to Kahurangi.

Relation to Underlying Units, Age, Interpretation

The contact with the underlying Turimawiwi Member is gradational at Kahurangi, and sharp at Te Hapu. At Abel Head the Rakopi Member is interbedded with the

Kaihoka Member, and forms sharp underlying contacts.

The Rakopi Member is of Duntroonian age at Abel Head (S1/501); at Te Hapu and Kahurangi, ages of underlying and overlying Turimawiwi and Paturau Members indicate a Whaingaroan age (see Fig. 2.3).

The gradational contact (Kahurangi) is interpreted as representing continuous sedimentation in a shelf environment; the sharp contacts (Te Hapu, Abel Head) are interpreted as minor paraconformities in inner shelf and nearshore environments.

TAKAKA LIMESTONE

The name Takaka Limestone was proposed by Grindley (1971) for well bedded limestones, sandy and gritty towards the base, and muddy towards the top, in the Takaka area (Type Section Tarakohe). It is proposed to include a micritic fine calcarenite originally included in the Abel Head Formation (Bishop 1971) as the lower member of the Takaka Limestone (see proposals for revision).

PATURAU MEMBER

Name, Description, Type Section, Distribution

The name Paturau Member, is proposed for 20 metres of massive and bioturbate lithologies ranging from silty, glauconitic, fine calcarenite to micritic, fine calcarenite limestones outcropping at Te Hapu (Type Section M25 696683). At the type section, the massive character of the Paturau Member persists for six metres, whereupon a change to alternating resistant and less resistant beds of 30-60 cm thickness occurs. Resistant beds have a high micrite content and less detrital silt than less resistant lithologies (see Composition).

Relation to Underlying Units, Age, Interpretation

The contact with the underlying Rakopi Member is gradational, occurring over several metres at Kahurangi and within 0.25 metres at Abel Head.

Foraminiferal samples from the Paturau Member, and immediately overlying and underlying members, suggest a Duntroonian age at Kahurangi (UC 7976, UC 7975), Duntroonian to Waitakian(?) age at Te Hapu (UC 7946, UC 7940) and Waitakian age at Abel Head (S1/519).

The Paturau Member is interpreted as representing low energy carbonate shelf deposition (see Interpretation).

ANATORI MEMBER

Name, Description, Type Section, Distribution

The name Anatori Member, is proposed for ten metres of bedded medium-coarse calcarenite : sandy echinoid-bryozoan-foraminiferal biosparite, outcropping at Te Hapu (Type Section M25 696683). The Anatori Member extends from Kahurangi, where it is 50 metres thick, to Abel Head where it is 4 metres thick. From Cape Farewell to Kahurangi allochemical and detrital content varies, some lithologies are micritic, others range up to fine calcirudite (see Structures and Textures, Composition).

Relation to Underlying Units, Age, Interpretation

The Paturau Member grades into the Anatori Member over several metres.

The base of the unit is of lower Duntroonian age at Kahurangi (UC 7996), of probable Waitakian age at Te Hapu (UC 7946) and of probable Otaian age at Abel Head (S1/520).

The Anatori Member is interpreted as representing shallow carbonate shelf sedimentation (see Interpretation).

CHAPTER III

SEDIMENTARY STRUCTURES AND TEXTURES

Associations of primary structures and textural features exhibited by the Pakawau Group, the Te Hapu, Kaihoka, Lighthouse and Anatori Members (Abel Head Formation and Takaka Limetone) are described. In the absence of primary structures in the massive and bioturbate Kaihoka, Turimawiwi, Rakopi and Paturau Members, textural features and lebenspurren characteristics are described. Grain size data (referred to in the following sections) and paleocurrent data are respectively presented in Figures 3.10 and 3.13.

PAKAWAU GROUP

Massive and Stratified Conglomerates, Conglomeratic Sandstones

In the Farewell Formation (Abel Head lithotope), polymodal, clast to matrix supported pebble-cobble conglomerates up to ten metres thick form tabular units of undetermined extent (probably hundreds of metres); similar lithologies of one metre thickness lens -out over fifty metres. Thin, fine pebble conglomerates from one to several clasts thick line the base of small scale channels, occur at the base of planar cross-stratified sandstones, or are interbedded with sandstone lithologies.

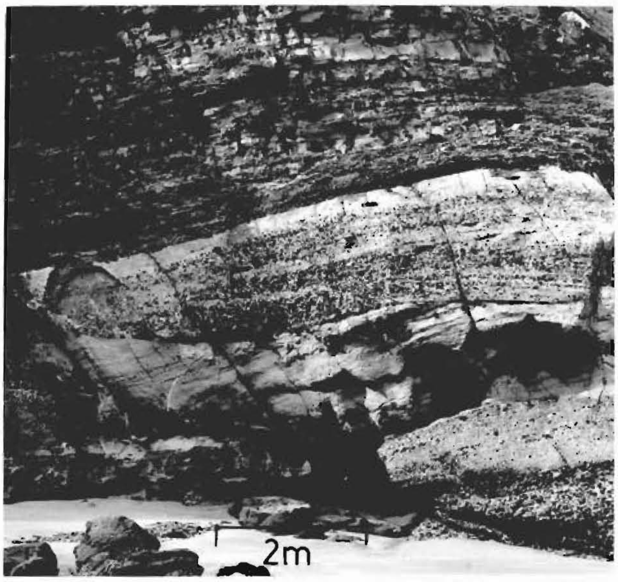
Conglomerates are mostly massive, with local thin lenses of horizontal or cross-stratified sandstones. Poorly defined stratification is mostly horizontal or subparallel channel bases (Fig. 3.1). Imbrication is rare. Pebble-cobble sandstones exhibit planar or trough cross-stratification.

Perigenic mudstone clasts (i.e. clasts derived from penecontemporaneous erosion of mudstones) ranging from cobble to boulder size, and sparse coalified branches occasionally occur at the base of conglomeratic units.

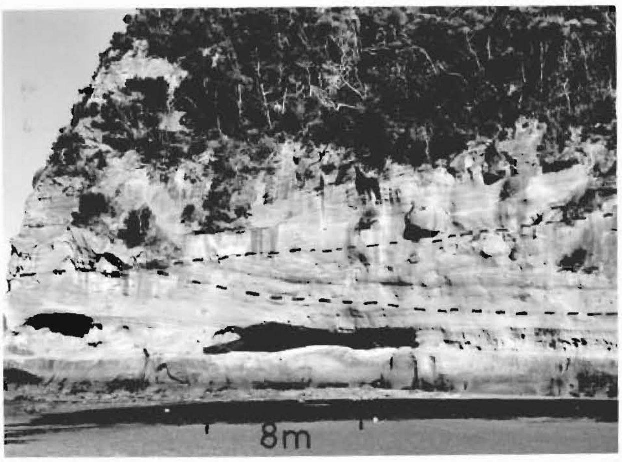
Massive and crudely stratified conglomerates are formed by a clast by clast accretion process during the formation of longitudinal bars, possibly under conditions of very high energy flow (Rust 1972); stratification probably results from discharge variation (Miall 1977). Trough and planar cross-bedded conglomeratic sandstone are respectively formed by filling of minor channels and migration of linguoid bars (Miall 1977).

Channels, Channel-Fill Cross-stratification

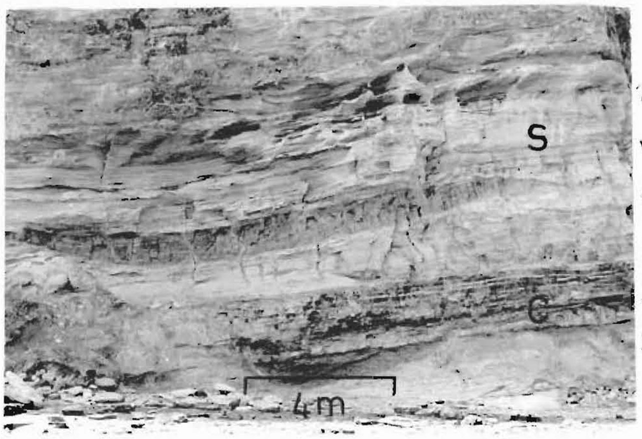
In the North Cape and Farewell Formations, small scours and channels range from one to at least seventy metres width (Fig. 3.1), channels average ten to twenty metres width and three to four metres thickness in cross section. Irregular erosional surfaces without a concave cross section are interpreted as lenses of channel structures with dimensions too large to be detected within a single outcrop. Lensoid mudstone units (1-3 m thick) overlying irregular or concave upward surfaces are interpreted as mud filled abandoned channels (Fig. 3.1).



a) Channel with stratified conglomerate infilling immediately below Te Hapu (T) - Nguroa Member (N) - Farewell Formation (F) contact, Kaihoka.



b) Low angle channel-fill cross-stratification of broad large scale channel, upper North Cape Formation, Whanganui Inlet.



c) Abandoned channel infilled with mudstone (dark lensoid unit centre of figure) in sandstone (S), coaly (C) and mudstone lithologies, middle North Cape Formation, Whanganui Inlet.

Fig. 3.1 Channel structures, North Cape and Farewell Formations

Near the base of an infilling sequence, stratification parallels the erosional surface, whereas further from the base stratification conforms less with the erosional surface and is horizontal.

Horizontal Stratification, Massive Sandstones

Horizontal stratification occurs in fine-coarse sandstones; massive or poorly defined stratification is commonly exhibited by medium sandstones to granule conglomerates.

In the North Cape Formation, medium-coarse sandstones, averaging ten to fifty centimetre thickness (Fig. 3.2), with low angle (5^{o}) cross stratification that subparallels broad erosional scours, gradually passes into sandstones with horizontal stratification. Medium-coarse sandstones with horizontal or low angle channel fill cross-stratification are commonly overlain or gradually pass into fine sandstone with horizontal stratification, thin siltstone drapes,[1] or alternating fine sandstone-mudstone lithologies.

In the Puponga Formation, fine-medium sandstone units up to one metre thickness and exhibiting horizontal stratification, gradually pass into, or are interbedded with massive medium sandstones, or thin siltstone units.

In the Farewell Formation, fine-medium sandstones with horizontal stratification and massive granule-coarse sandstones, are interbedded with cross-stratified sandstones and conglomerates.

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[1]The term 'drape' is used to denote silty or clayey units whose upper and lower surfaces conform to the shape of the underlying bedform.

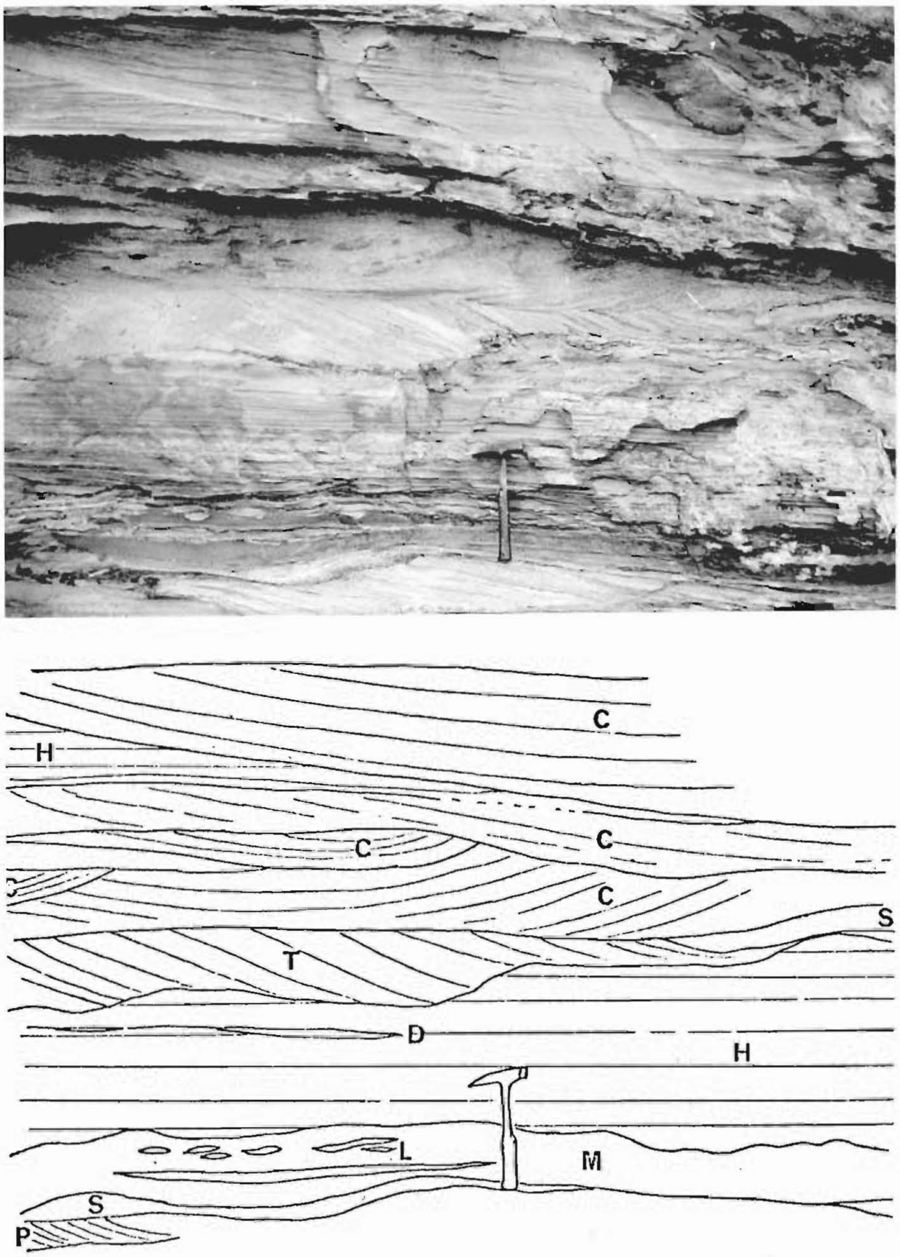


Fig. 3.2 Channel-fill (C), planar (P) and intermediate planar-trough (T) cross-stratified sandstones, siltstone drapes (D) and mudstones (M) with lenticles, lenses of fine sandstone (L), North Cape Fm., Whanganui Inlet. Hammer length is 32cm.

Horizontal stratification has been interpreted as representing planar bed flow under low to upper flow regime conditions (Harms and Fahnestock 1965, Harms *et al.* 1975). An alternative interpretation (Jopling 1966) proposes that horizontal stratification is a response to gradual upward shift in the profile of equilibrium, as a result of a change in one or more variables characterizing a sediment transport system, or a shift in local base level.

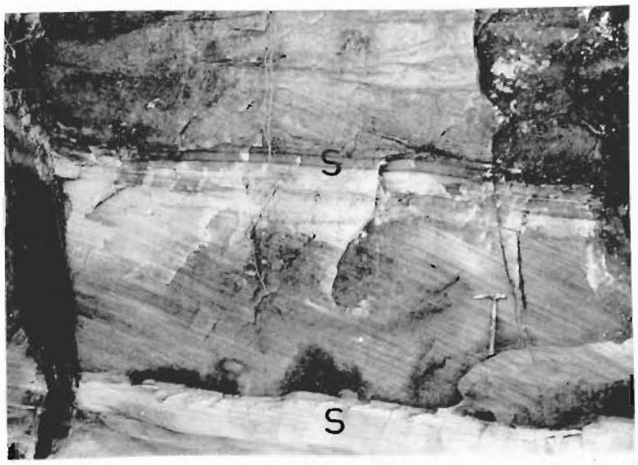
Large Scale Trough and Planar Cross-stratification

Large scale cross-stratification (units 5 cm to one and a half metres thickness) occurs in granular, very coarse to medium sandstone lithologies of the North Cape and Farewell Formations. Cross-stratified units are commonly ten to twenty-five centimetres thick and include planar, tabular and trough cross-stratified sets (terminology of McKee and Weir 1953) and intermediate forms with slightly irregular bases (Fig. 3.3). In some instances, planar cross-stratified units up to one metre thick occur (Fig. 3.3). Foresets range from planar to concave.

In the North Cape Formation, trough types occur as solitary scoops or cosets of mutually cross cutting troughs, and planar and intermediate types most commonly occur as multiple sets (Fig. 3.3). In the Farewell Formation, planar cross-stratification occurs as multiple or solitary sets with ripple trains up to seven metres long.

Trough cross-stratification results from infilling of scours by megaripple or dune migration under lower flow regime conditions. Planar cross-stratification represents

a) Multiple sets of cross-stratified very coarse-coarse sandstone, commonly with irregular bases, and intermediate in character between trough and planar cross-stratification, upper North Cape Formation. Hammer length is 32 cm.
Printed from colour slide.



b) Thick (1 m) planar cross-stratified very coarse-coarse sandstones with interbedded horizontally stratified sandstone and massive siltstone (S), middle North Cape Formation. Hammer length is 32 cm.
Printed from colour slide.

c) Trough (T) and channel-fill (C) cross-stratified granular coarse sandstones with silt lined scour channels (S) and intraformational conglomerate (I), middle North Cape Formation. Hammer length is 32 cm.
Printed from colour slide.

Fig. 3.3 Large-scale cross-stratification types,
Pakawau Group, Whanganui Inlet

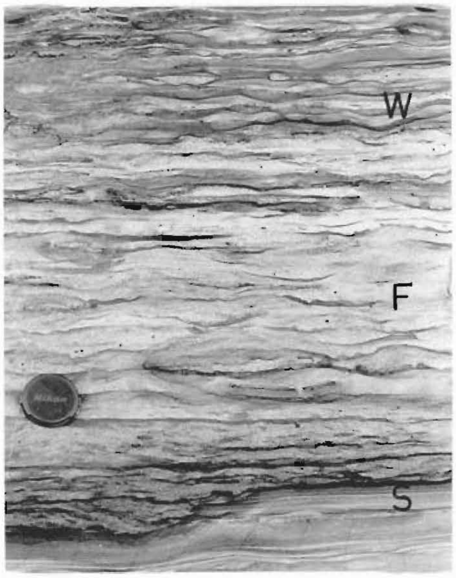
megaripple and linguoid bar migration under upper flow regime conditions (Miall 1977). Jopling (1966, see also horizontal stratification) interprets planar cross-stratification as a response to a relatively large and upward shift in the profile of equilibrium.

Small Scale Ripples and Trough Cross-stratification

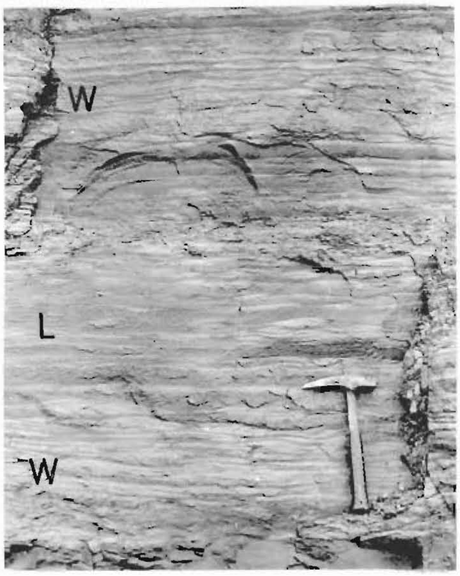
Small scale ripple bedforms occur with and without obvious cross-lamination. Small scale ripples and trough cross-stratified fine sandstones are interbedded with mudstones, and form a continuum of lenticular to flaser bedded types in the North Cape Formation (Fig. 3.4). Small scale ripples and trough cross-stratified fine sandstones are less common in the Puponga Formation, and rare in Farewell Formation lithologies.

Climbing-ripple lamination with lee side of ripples preserved (Type 2 laminae in drift, Jopling and Walker 1968) is commonly associated with horizontally laminated fine-medium sandstone (Fig. 3.5). Climbing-ripples with lee and stoss sides preserved (Type 1 laminae in-drift and laminae in-phase, Jopling and Walker 1968) are comparatively rare and pass gradually into massive fine sandy siltstones (Fig. 3.5).

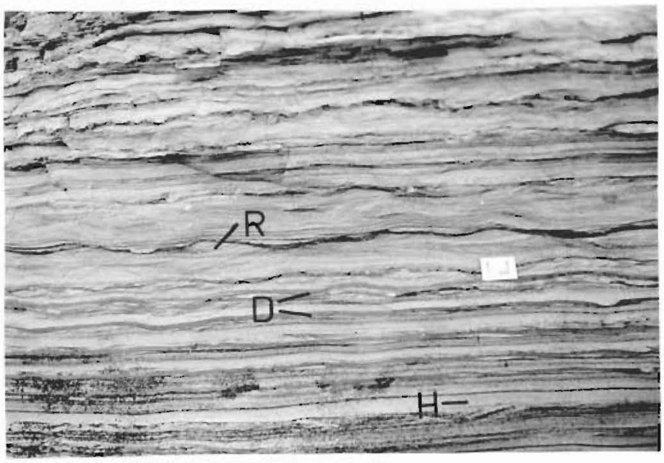
Small scale ripples form under low flow regime conditions (Harms and Fahnestock 1965); climbing-ripples indicate rapid accumulation (McKee 1966). Type 2 climbing-ripples indicate conditions of higher bed load / suspension load than Type 1 climbing-ripples (Jopling and Walker 1968).



a) Wavy (W) and flaser (F) bedding, and siltstones with thin even fine sandstone laminations (S), lower North Cape Formation. Lens cap diameter is 5.5 cm.

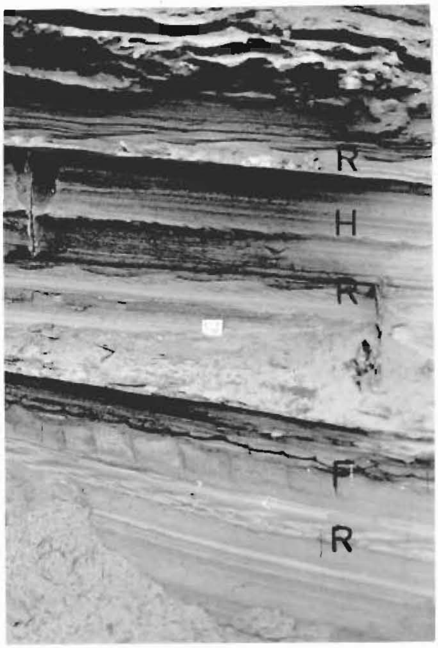


b) Wavy (W) and lenticular bedding (L) in alternating sandstone-mudstones, lower North Cape Formation.
Hammer length is 32 cm.
Printed from colour slide.

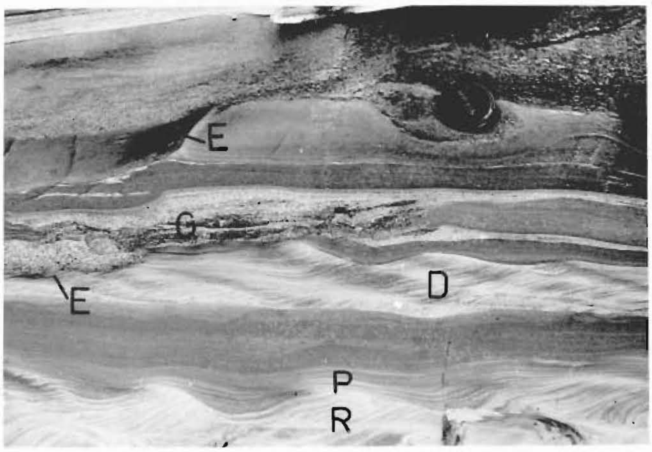


c) Evenly and horizontally laminated fine sandstone (H) and small scale ripples (R) with siltstone drapes (D), lower North Cape Formation.
Scale is 2 cm.
Printed from colour slide.

Fig. 3.4 Alternating sandstone-mudstone bedding types, Pakawau Group, Whanganui Inlet



a) Climbing-ripples (R), horizontally stratified fine-medium sandstones (H), massive and laminated siltstones (S) and flame structures (F), middle North Cape Formation. Scale is 2 cm.



b) Climbing-ripples 'in-drift' (D), and ripples (R) in transition to climbing-ripples 'in-phase' (P) and massive siltstone. Erosional scours (E) infilled with granular very coarse sandstone (G), North Cape Formation. Lens cap diameter is 5.5 cm.

Fig. 3.5 Climbing-ripple types and associated siltstone-sandstone bedding types, Pakawau Group, Whanganui Inlet

Fine sandstone and fine sandstone-mudstone bedding

Massive muddy fine to very fine sandstone is a common feature of the finer lithologic associations of all formations. Fine sand is occasionally concentrated as discontinuous laminae, and grading with respect to mud content is expressed by light to dark colour variation. Massive lithologies are sometimes associated with load-casts (Fig. 3.6). Massive claystones, siltstones and clayey siltstones with parallel laminated fine sandstone interbeds are common in the Farewell and upper North Cape Formations.

Alternating fine sandstone-mudstone bedding types include evenly interlayered sand/mud bedding, flaser, wavy and lenticular bedding (Fig. 3.4). Evenly interlayered sand/mud units range from two to eight centimetres thick; sand/mud transition is sharp or gradational. This association is common in the North Cape Formation and generally absent in the Farewell Formation.

Massive or parallel laminated siltstones with occasional fine-medium sandstone lenticles, or parallel laminated fine sandstones with occasional thin siltstone drapes, are common in the Puponga and Farewell Formations.

Graded fine sandstone to mudstone lithologies represent a gradual transition from lower flow regime to deposition from suspension; flaser, lenticular and wavy types indicate distinct intervals of lower flow regime traction and deposition from suspension.

Soft sediment deformation structures

In the North Cape Formation, load-casting has produced incipient ball-and-pillow structures (Fig. 3.6),

a) Attenuated intraformational ('perigenic') conglomerate clasts (I) and laminated coarse sandstone (L) grading into massive siltstones with coarse sandstone pillow structures (P), North Cape Formation. Lens cap diameter is 5.5 cm.

b) Sandstone dyke cutting siltstone with thin sandstone interbeds, upper North Cape Formation. Scale is 2 cm.

c) Convolute lamination in fine sandstones, North Cape Formation. Hammer length is 32 cm.

Fig. 3.6 Soft sediment deformation structures, Pakawau Group, Whanganui Inlet.

and flame structures one to two centimetres in height that project from fine sandstone/mudstone into fine-medium sandstone lithologies. Convolute lamination is occasionally exhibited by thin interbedded fine sandstone and massive siltstone or muddy fine sandstone lithologies, and horizontally stratified fine-coarse sandstones (Fig. 3.6). Sandstone dykes (½ - 4 cm wide) are commonly associated with disrupted bedding in siltstone-fine sandstones and massive medium-coarse sandstones (Fig. 3.6).

Liquefaction of sandy lithologies has been attributed by Coleman (1969) to increased shear stress produced by increasing velocities, emergence of depositing surfaces, and currents heavily laden with fine grained sediments. Load-cast structures result from deposition of sand over a hydroplastic layer (Reineck and Singh 1973).

ABEL HEAD FORMATION

NGUROA MEMBER

Sandy conglomerates, conglomeratic sandstones and conglomerates are massive and thin (10 cm to 1 metre). Generally well sorted, fine to cobble size gravel components are well rounded and do not show any morphologic differences with Pakawau Group gravels. Cobble to boulder conglomerates (1 metre thick) exhibit near maximum packing density (Abel Head, Anatori). Granule to pebble conglomerates (10 to 20 cm thick) are sandy and not as closely packed. At individual localities the Nguroa Member exhibits closer packing than the Pakawau Group (Abel Head), or is pebbly where the underlying Pakawau lithologies are sandy (Te Hapu, Sharks Head, Anatori Sections).

Variation in Nguroa Member lithologies represents varying winnowing effectiveness, a combination of energy expenditure and/or sand availability. Densely packed cobble-boulder conglomerates (Abel Head and Anatori Sections) represent extremely effective winnowing; sandy pebble conglomerates (Kaihoka, Te Hapu Sections) represent less effective winnowing.

TE HAPU MEMBER

The association of sedimentary structures and textures of the Te Hapu Member is distinct from other Abel Head Formation Members in that lithologies commonly exhibit original lamination and distinct bedding, the textural types are predominantly fine sandstone but include both conglomerates and mudstones, and thin fining upward sequences are developed (see Kaihoka, Te Hapu, Sharks Head, Anatori and Kahurangi Sections). Other Abel Head Formation Members are massive and do not exhibit a conglomerate to mudstone range of lithologies.

Conglomerates

Massive, well rounded and sorted pebble conglomerates, commonly overlying irregular surfaces up to 50 cm thick and lensing out over several metres, comprise minor lithologies in all sections. Rarely, gastropod and bivalve debris is incorporated within conglomerate lenses or occurs as thin

(3 cm) interbedded lenses in fine sandstones.

Granular very coarse-coarse sandstones

Well sorted and moderately rounded, and occasionally pebbly or granular, very coarse to coarse sandstones, range from evenly stratified units one grain to several centimetres thickness, up to regular massive lensing units with an average thickness of 10 cm. Granular very coarse sandstone lithologies commonly overlie thin conglomerates or erosional surfaces, or are interbedded with mudstone or sandstone lithologies.

Mud laminated fine sandstones

Muddy, well sorted, fine sandstones generally range from 25 to 50 cm thickness. Stratification is in the form of, and ranges from, mud laminations (i.e. less than 1 cm), to thick (2 cm) and diffuse mud concentrations spaced from several to 10 cm (Fig. 3.7). Stratification types include horizontal and low angle channel-fill cross-stratification and wavy and even stratification parallel to irregular erosional surfaces. Mud laminated fine sandstones commonly overlie coarse sandstones or conglomerate lithologies, or are separated from a similar lithology by an erosional surface or thin intervening mudstone. Mud laminated sandstones commonly pass transitionally into interlayered fine sandstone-mudstone types (Fig. 3.7).

Thinly interlayered fine sandstone-mudstones

An association of thin lenticular bedding, and even and horizontally interlaminated fine sandstone-mudstones (Figs 3.7, 3.8) commonly grade into thin dark mudstones

(Fig. 3.7). Occasional thin dark mudstones (1-2 cm) are interbedded in fine sandstone lithologies.

Massive fine sandy mudstone-fine sandstones

Massive, intensely bioturbate lithologies range from fine sandy mudstone to fine sandstone. Occasional remnant laminations indicate the lithologies were originally mud laminated fine sandstones and thinly interlayered fine sandstone-mudstone types (described above). Coarse sand has infilled burrow structures and subsequent biogenic reworking disseminated coarse sand grains.

Upward fining sequences

Upward fining sequences commonly consist of mud laminated fine sandstones passing transitionally into thinly interlayered sandstone-mudstones (Fig. 3.7). Fine sandstones are occasionally underlain by coarse sandstone or conglomerate; the basal contact is often irregular or forms low angle cross-cutting relationships, and overlying lithologies parallel the basal contact.

Interpretation of Te Hapu Member lithologies

Thinly interlayered fine sandstone-mudstones are interpreted as representing minor alternations, suspension and lower flow regime migration of extremely flattened, small scale ripples (Reineck and Singh 1975, p.109).

Mud laminated fine sandstones that pass transitionally into thin interlayered fine sandstones-mudstones are interpreted as lower flow regime deposits. Coarse sandstones, conglomerates and erosional surfaces represent higher flow conditions. Upward fining sequences are interpreted as representing declining flow conditions and channel filling. Intensely bioturbate lithologies are interpreted as representing subenvironments with low sedimentation rates in marine situations.

KAIHOKA MEMBER

Fine pebble conglomerate

Massive, fine pebble conglomerates, ranging from ten centimetres to two metres thick, form a minor proportion of Kaihoka Member lithologies. At Kaihoka and Te Hapu (sections back pocket), a 30-50 cm thick pebbly sandstone passes transitionally to and from a massive, coarse sandstone and contains rounded concretionary fine sandstone clasts of cobble to boulder size (Fig. 3.9).

At Kahurangi several packed, well sorted and rounded pebble conglomerates 10-50 cm thick are interbedded and form sharp contacts with laminated fine sandstone (Fig. 5.10). At the top of the Kaihoka Member, a one metre thick, fine pebble conglomerate passes transitionally to and from sandy siltstone and siltstone. In the lower silty part, fine pebbles and coarse sand occur as discontinuous lenses or infill anastomosing *Ophiomorpha* burrows (Fig. 3.8).

Massive granular, very coarse-coarse sandstones

The predominant lithology of the Kaihoka Member consists of massive granular, very coarse to coarse sandstones that range from thin, irregular lenses of 10 cm thick (Kahurangi Section) to units up to several metres thick (Te Hapu, Abel Head Sections, Fig. 5.10, back pocket).

Granule to coarse sand size grains are generally well rounded (Fig. 3.12; cf. Pakawau Group sand grains Fig. 4.15) and well sorted (Figs 3.10g,h; cf. Pakawau Group Figs 3.10i,j,k). A strongly bimodal coarse and fine sandstone (Fig. 3.12b) occurring in the Abel Head Section is atypical. Grains are often matrix supported, a high matrix content ranging from silty clay to micrite recrystallized microsparite and sparite, is in part due to large interstitial space between very coarse grains.

Evenly laminated fine sandstones

Even and parallel laminated, well sorted fine sandstones form beds 50 cm to several metres thick. Lamination is generally horizontal, but occasionally forms cross-stratification in channel-fill structures up to several metres wide (Fig. 3.7). At Kahurangi, mica occurs in laminations and broad and diffuse concentrations (2-4 cm).

Interpretation of Kaihoka Member lithologies

Even lamination can form by swash and backwash action of waves in the wind regime, by plane bed movement in the upper flow regime, and below small scale ripple formation in the lower flow regime (Reineck and Singh 1975).

The Kaihoka Member exhibits a number of 'textural inversions' (Folk 1968). The high rounding and sorting of granular coarse sands is indicative of high energy expenditure over a protracted period or a high energy environment. This is inconsistent with a high matrix content of some samples, and a final low energy environment of accumulation with extensive bioturbation is suggested.

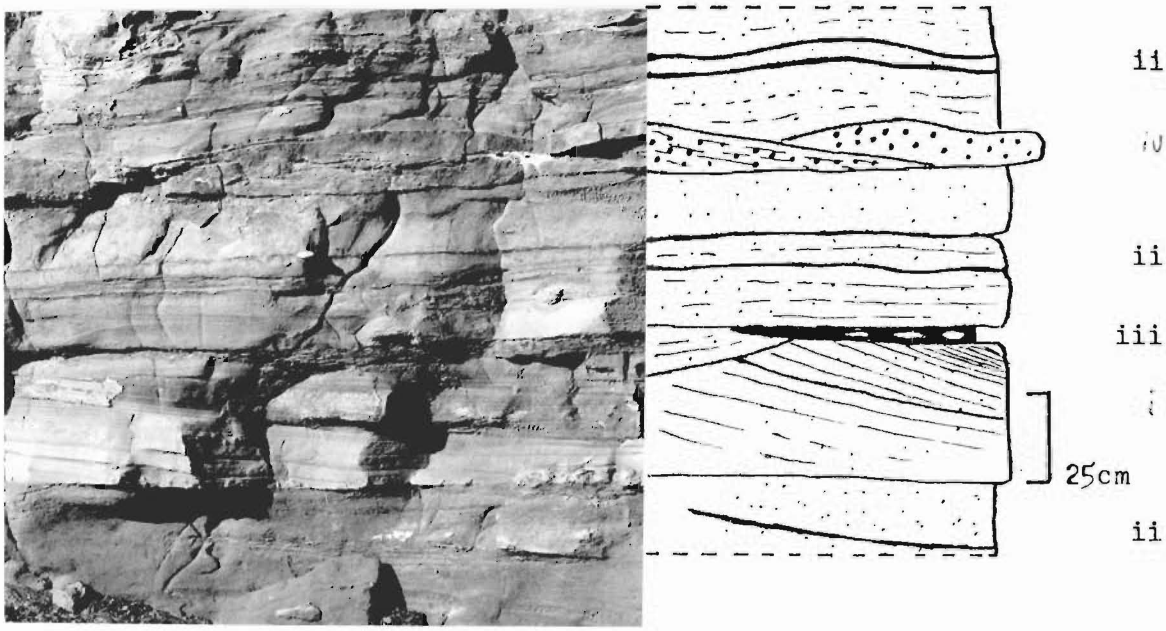
Similarly, in a silty, coarse sandy pebble conglomerate (Kahurangi Section), sorting and rounding of coarse sand and fine pebbles is inconsistent with a silty matrix. Coarse sands and fine pebbles, previously rounded and sorted in an environment of high energy expenditure, have been reworked into a low energy environment as thin interbedded lenses and have filled open burrows; subsequent burrowing has disseminated coarse sand and fine pebbles. The bimodal sandstone (Fig. 3.12b) is interpreted to be a result of biogenic mixing (at the Kaihoka, Te Hapu and Kahurangi Sections, thin interbeds of fine sandstone occur in coarse sandstone lithologies).

Packed, rounded and sorted conglomerate (Kahurangi Section) with sharp contacts, indicate a high energy environment and effective winnowing processes.

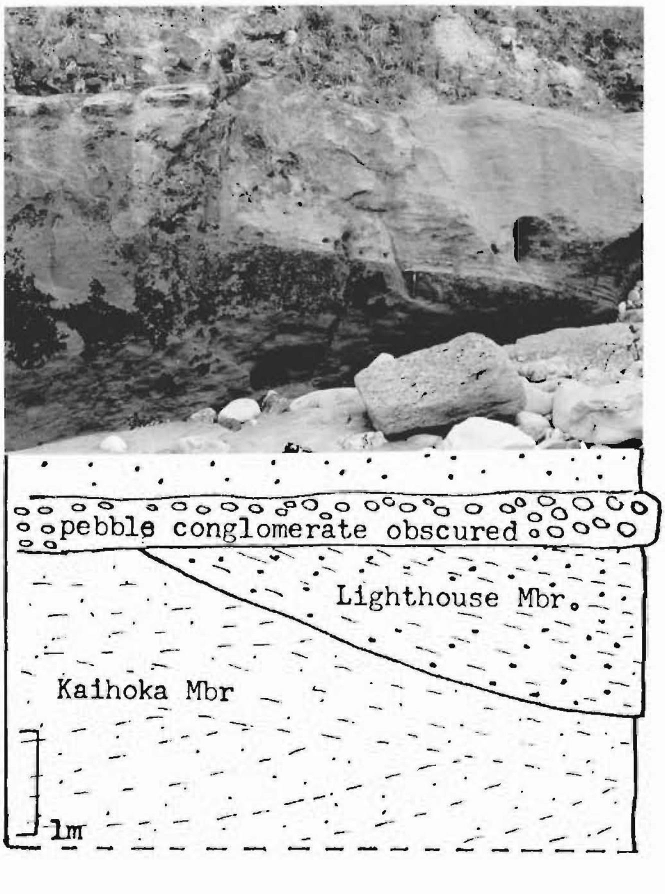
LIGHTHOUSE MEMBER

A solitary channel structure with channel-fill cross-stratified granular coarse sandstone is incised into the Kaihoka Member (Alva Ck - Big R. Section at Kahurangi, Fig. 3.7). At the only other known outcrop (south of Lighthouse Section at Kahurangi), large scale channel-fill and multiple sets of planar, cross-stratified, massive and horizontally stratified granular, very coarse to coarse sandstones occur. Carbonised wood fragments and intra-formational siltstone clasts occur at the base of a cross-stratified unit. Granular, very coarse to coarse sandstones are moderately rounded and sorted.

Structural and textural characteristics resemble

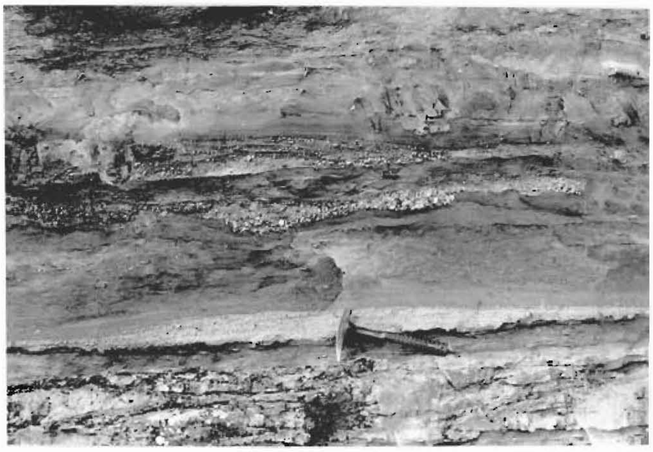


a) Te Hapu Member. (i) Mud laminated fine sandstones with low angle channel-fill cross-lamination grading into thin even alternations of mudstone and fine sandstone; (ii) thin mudstones in fine sandstone, massive or with poorly defined lamination; (iii) lenticular bedding; (iv) massive and stratified coarse sandstone, Sharks Head Beacon.

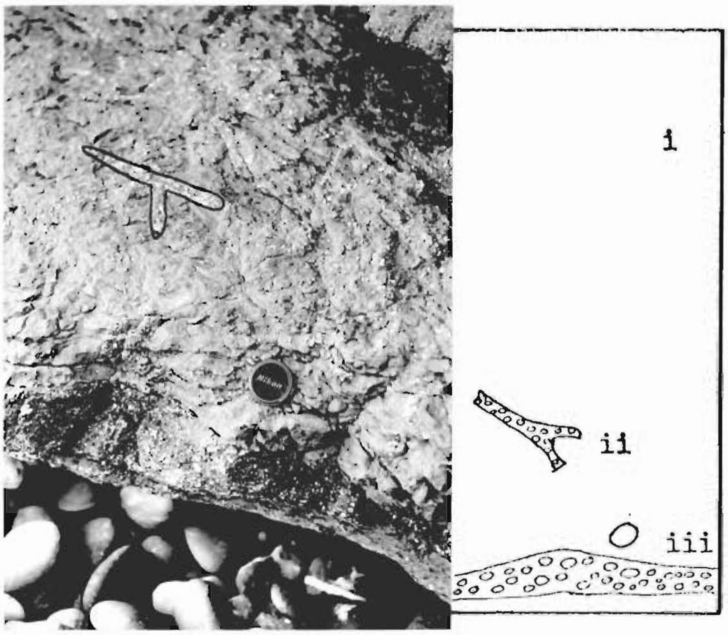


b) Lighthouse Member, channel-fill cross-stratified coarse sandstones cutting horizontal and channel-fill cross-stratified Kaihoka Member fine sandstone, Kahurangi.
Printed from colour slide.

Fig. 3.7 Channel-fill cross-stratification, Te Hapu, Lighthouse and Kaihoka Members.



a) Thin massive and crudely stratified granule pebble conglomerates overlying irregular erosional surfaces, Te Hapu Member. Hammer length is 30 cm. Printed from colour slide.

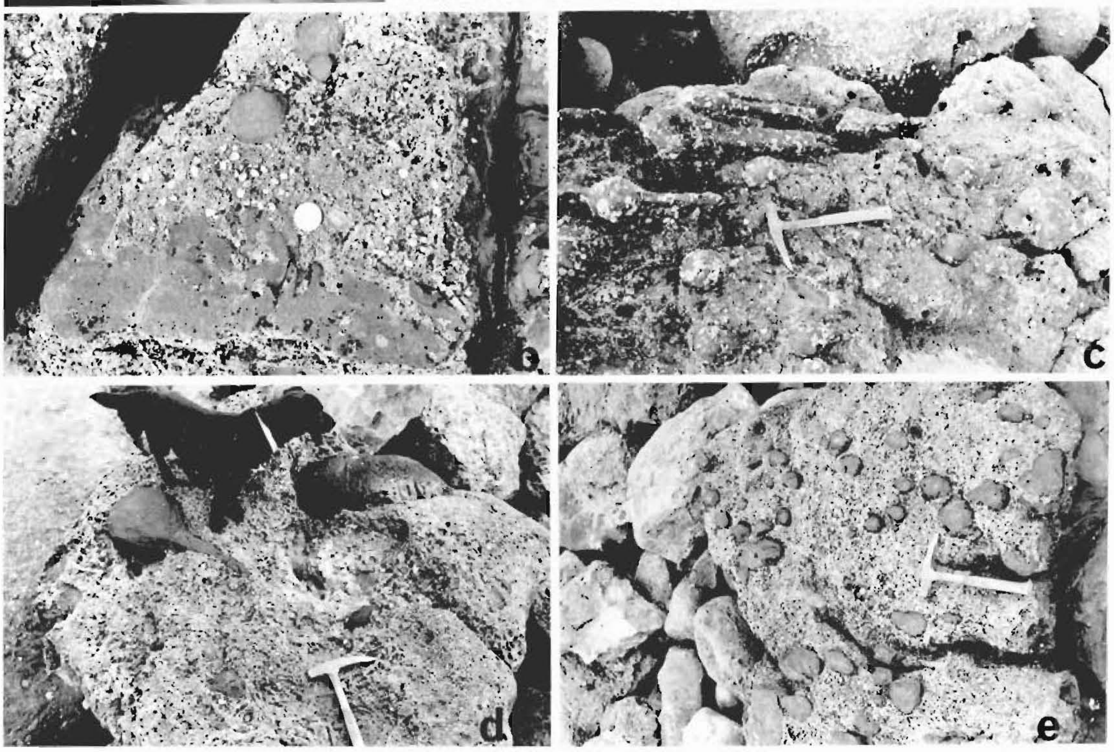


b) Fine pebble conglomerate.
i) dispersed in massive bioturbate silty lithology;
ii) concentrated in burrow;
iii) concentrated in irregular lens, Kaihoka Member. Lens cap is 5.5 cm diameter.

c) Evenly interlaminated fine sandstones-mudstones with minor bioturbation, Te Hapu Member. Coin diameter is 3.0 cm.

Fig. 3.8 Alternating fine sandstones-mudstones, Te Hapu Member, and fine pebble conglomerates, Te Hapu and Kaihoka Members.

a) Massive, pebbly, very coarse sandstone overlying horizontally stratified sandstone with sand infilled burrows and concretions (casts lower left). Figs. b), c), d) and e) illustrate morphologic variation of concretions. Hammer length = 32cm, lense cap diameter = 5.5cm, coin diameter = 3cm. Fig. f) illustrates the inferred genesis and subsequent reworking history of the concretions.



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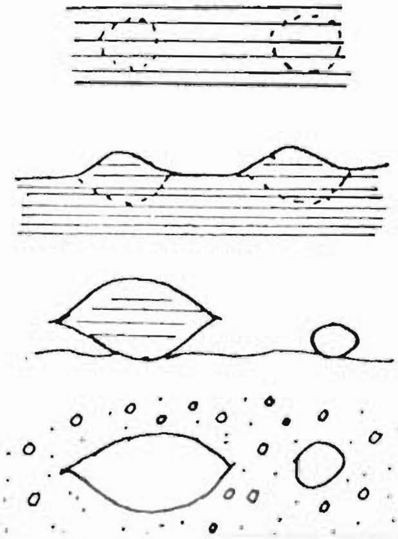


concretion formation in parallel and horizontally laminated fine sandstone, see (a)

reworking and removal of unconsolidated sands from around resistant concretions, see lower (b), (c)

concretions concentrated as lag in pebbly-very coarse sandstones, see (d), (e)

Fig. 3.9 Spheroidal sideritic concretions, associated structures and inferred reworking history, Kaihoka Member, Te Hapu those found in granule conglomerate-coarse sandstone lithologies of the Pakawau Group.

TURIMAWIWI AND RAKOPI MEMBERS

The Turimawiwi and Rakopi Members are generally massive. Muddy, fine sandy siltstones comprise the bulk of the Turimawiwi Member; near the base muddy, fine siltstones contain well rounded and very course to coarse sands (Fig. 3.12d). The Rakopi Member ranges from coarse sandy glaucarenite to fine sandy glaucarenites. Both have a micrite or microspar (aggraded from micrite) matrix. Generally a glauconite coarse sand mode is associated with a high micrite-microspar content, and a glauconite fine sand mode is associated with an increase in detrital coarse sand (cf. Fig. 3.10c, Fig. 3.10d). Thin, irregular, lensoid interbeds of coarse sand from 2-10 cm thick occur near the base of the Turimawiwi Member (Kahurangi, Te Hapu Sections). At Te Hapu up to 40% well rounded and sorted coarse sand grains and fine-medium sand size glauconite grains are disseminated throughout the lithology, or concentrated in burrows.

Interpretation of Turimawiwi, Rakopi Members

The presence of burrows and vestiges of an original lamination indicates massiveness is a secondary feature resulting from intense bioturbation. A low energy environment is suggested by clayey-silt and micrite sedimentation. Coarse sands, previously rounded and sorted in an environment of high energy expenditure, have been reworked into a low energy environment as interbedded thin lenses, and have filled open burrows; subsequent burrowing has disseminated coarse sand grains.

TAKAKA LIMESTONE

Massive fine calcarenites

The Paturau Member is a massive fine calcarenite (Fig. 3.11), with micrite-microsparite matrix/recrystallized matrix. Micrite-microsparite ranges from 15% to 40% in distinct interbeds up to 50 cm thick (Fig. 3.12f). A massive, fine-medium calcarenite in the upper part of Anatori Member is restricted to the Kahurangi vicinity.

Bedded medium-coarse calcarenites

The Anatori Member consists of medium-coarse calcarenite (Figs 3.11, 3.12g), with micrite-sparite matrix/cement (packstones and grainstones in Dunham (1962) terminology). The calcarenites are typically horizontally bedded, and both range from 4-12 cm thickness. At Kahurangi, irregular massive beds of 5-20 cm thickness, consisting of up to 40% granule-coarse sand size detrital grains, are interbedded with horizontal and planar cross-bedded units of 5-10 cm thickness.

Generally, the modal grain size of detrital grains is less than that of fossil allochems; for example, medium sand size allochems are associated with a fine sand size detrital mode (Fig. 3.11). Sorting of allochems and detrital grains ranges from moderate to well sorted (Fig. 3.11). Some echinoid plates are rounded

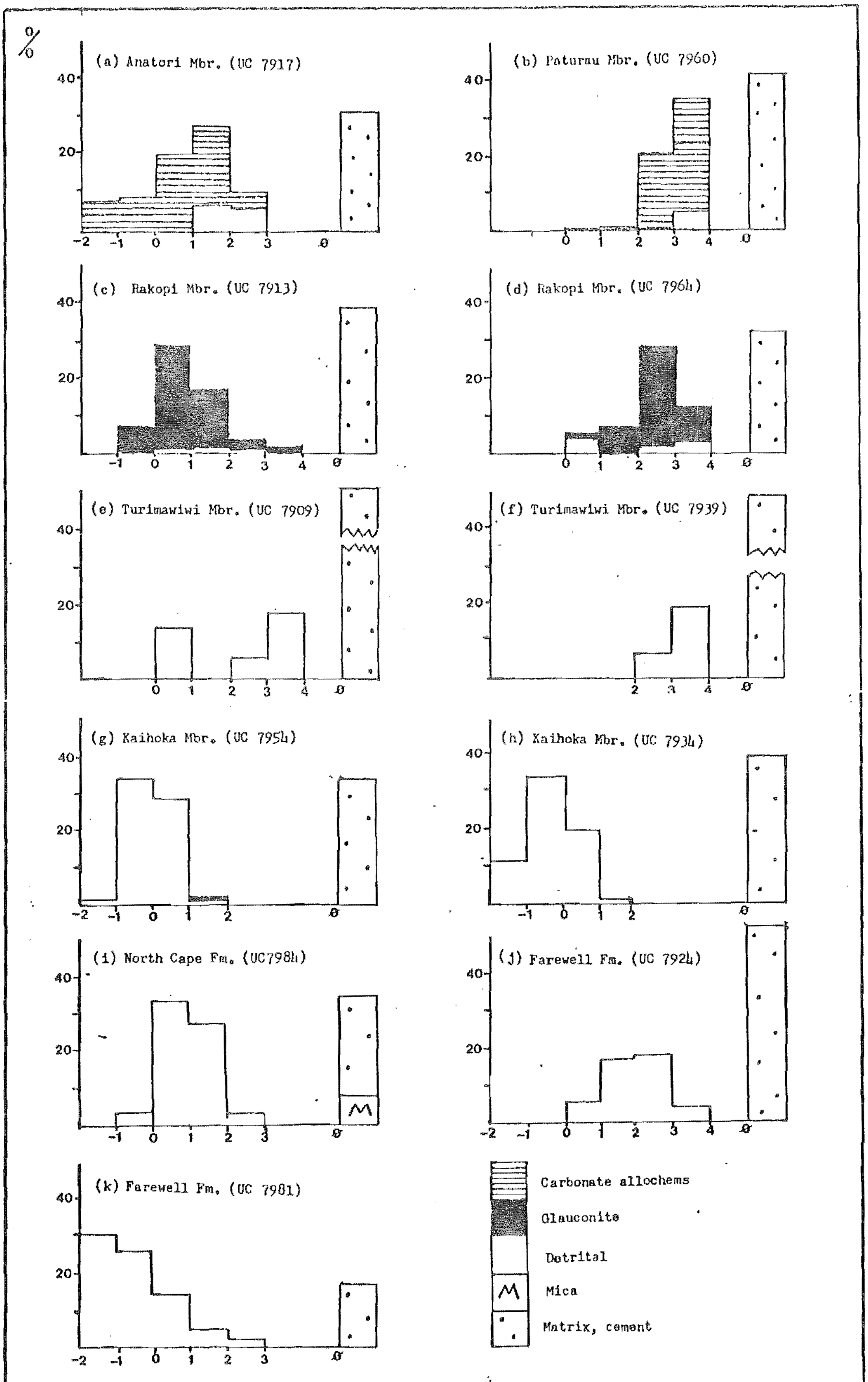


Fig. 3.10. Histograms comparing grain size distribution of Pakawau Group sandstones, Abel Head Formation and Takaka Limestone lithologies (determined in thin section).

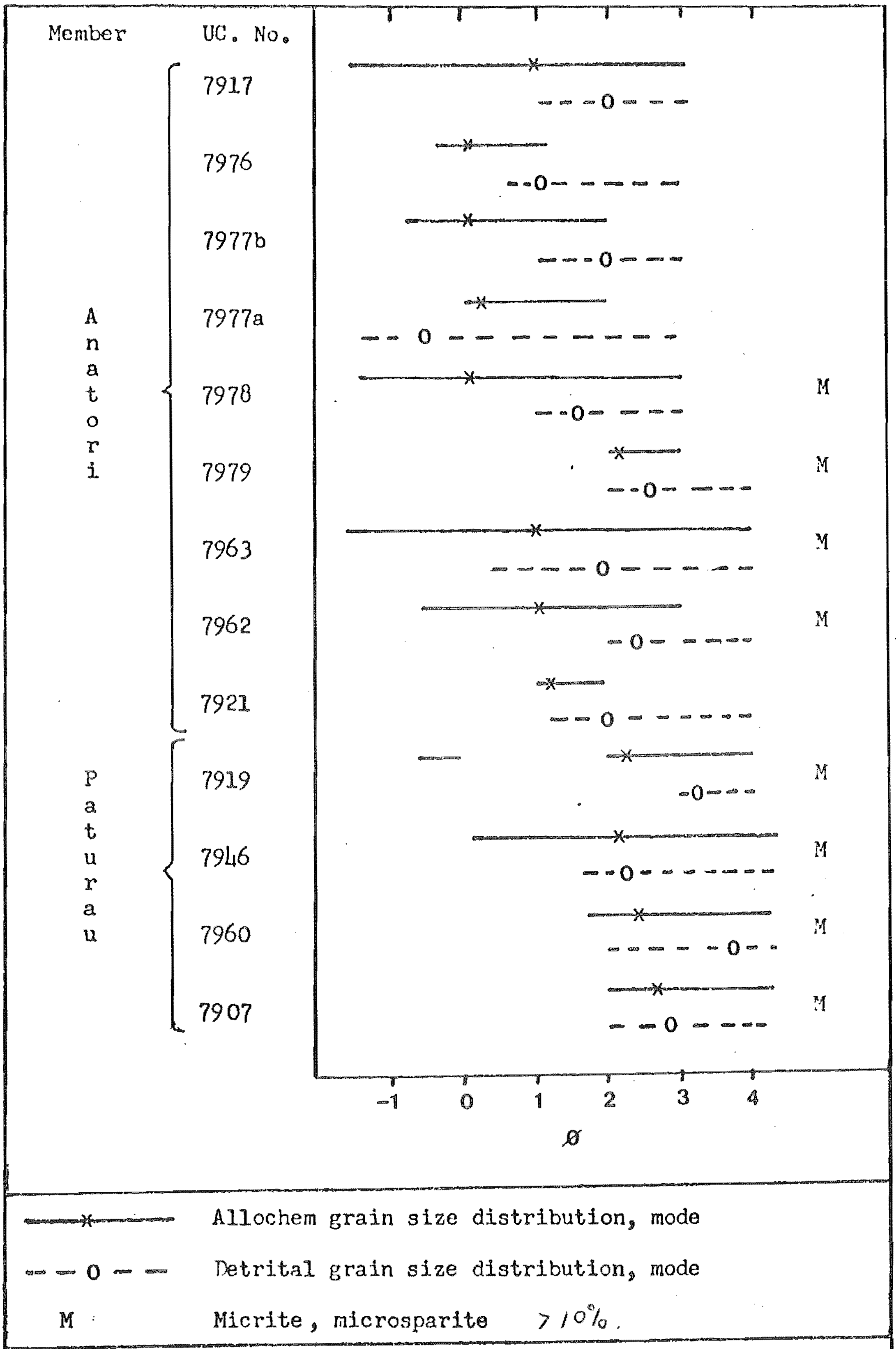
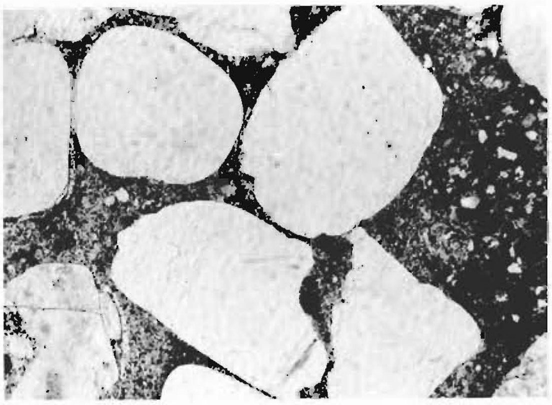
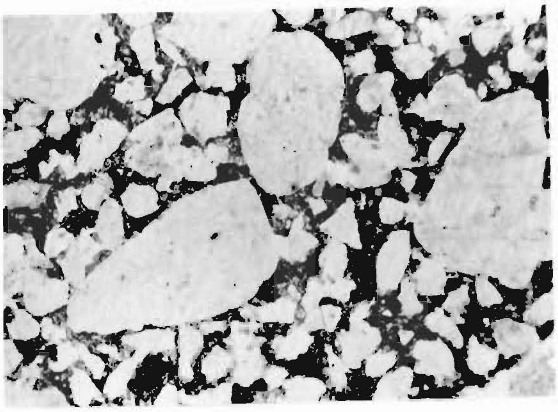


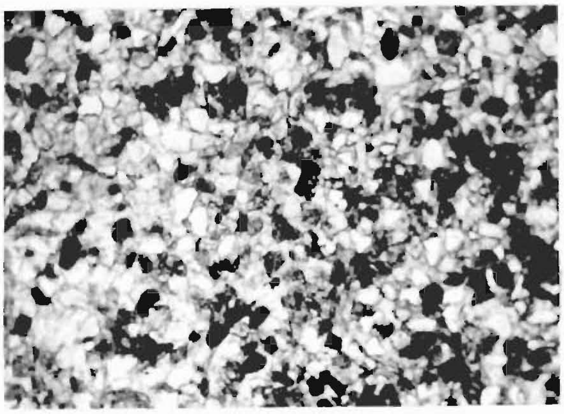
Fig. 3.11. Textural comparison of the Paturau and Anatori Members, Takaka Limestone.



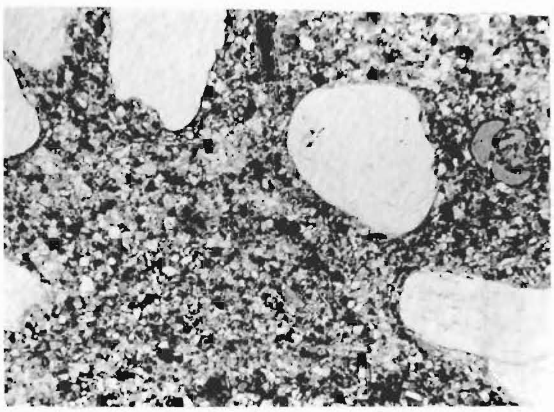
a) Kaihoka Member, well rounded and sorted very coarse-coarse sandstone with clayey silt matrix. Plane polarized light. UC 7957.



b) Kaihoka Member, bimodal, rounded very coarse-coarse sandstone and fine-medium sandstone. Plane polarized light. UC 7908.

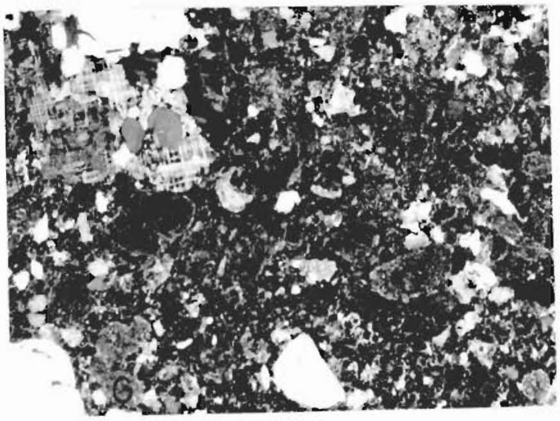


c) Kaihoka Member, well sorted fine sandstone. Dark grains are glauconite and ilmenite or magnetite. Plane polarized light. UC 7941 b.

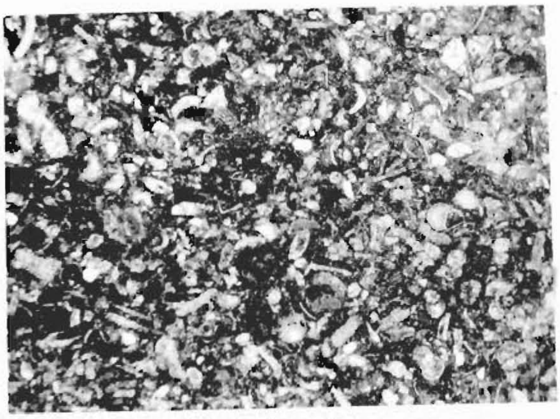


d) Turimawiwi Member, well rounded and sorted very coarse-coarse sands in clayey silty-very fine sandstone. Plane polarized light. UC 7948.

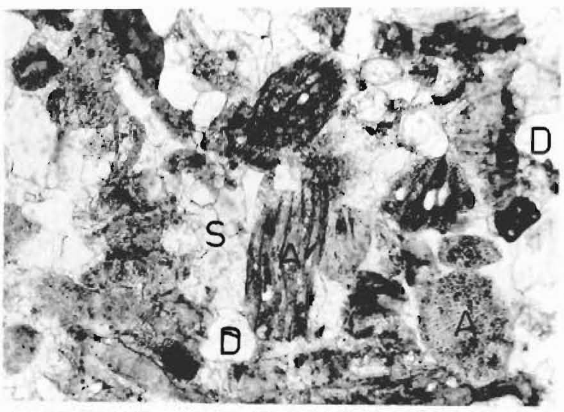
Fig. 3.12 Photomicrographs of textural features of Kaihoka and Turimawiwi Members.
(Field of view, all figures, is 2.25 mm)



e) Rakopi Member, sandy glaucarenite with micrite matrix, minor detrital silt. Detrital coarse-very coarse sand grains are well rounded, spheroidal-ovoidal glauconites (G) are fine sand size. Cross polarized light. UC 7950.



f) Paturau Member, fine calcarenite with micrite-microsparite matrix/recrystallized matrix. Plane polarized light. UC 7960.



g) Anatori Member, sorted coarse calcarenite with allochems (A), sparite cement (S), and well rounded medium sand size detrital grains (D). Plane polarized light. UC 7917.

Fig. 3.12 Photomicrograph of textural features of Rakopi, Paturau, Anatori Members (field of view, all figures, is 2.25 mm).

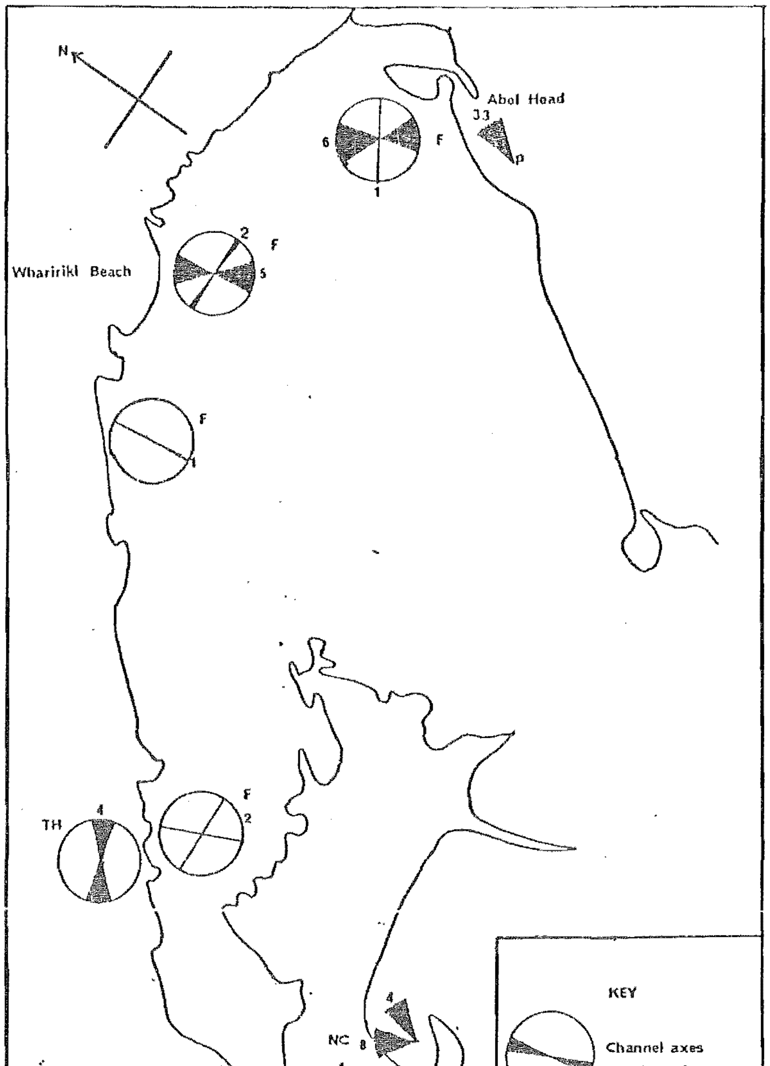


Fig. 3.13. Paleocurrent data for the Te Hapu Member, North Cape and Farewell Formations.

foraminiferal, bivalve, and bryozoan debris exhibits fragmentation with little evidence of rounding. Detrital grains range from angular to very well rounded (Fig. 3.12g).

PALEOCURRENT DATA

In the Pakawau Group, channel orientation data, supplemented by cross bedding measurements (and one set of pebble imbrications), indicate a general transport direction from the south-west to south-east quarter (Fig. 3.13). Channel orientations were obtained by assuming that the original strike of channel sides or of channel-fill cross-stratification, obtained by correction for depositional tilting (stereographic methods of Potter and Pettijohn 1963), paralleled the channel axis.

Channel orientations in the Te Hapu Member, extremely difficult to measure because of their location in vertical cliffs and the low angle of channel surfaces, indicate a general northeast-east/southwest-west transport direction (Fig. 3.13).

BIOGENIC STRUCTURES

The massive characteristics of Abel Head Formation lithologies is a result of intense bioturbation. Biogenic activity in Pakawau Group lithologies is extremely rare, and only two ichnogenera were recorded. Identification of ichnogenera is based on Häntzschel (1975), preservational aspects on the toponomic classification of Martinsson (1970), and life habits or behavioural patterns on the ethological classification of Häntzschel (1975) (after Seilacher 1953).

Ophiomorpha (Fig. 3.14)

Tubular burrows, 1-3 cm in diameter, commonly bifurcating, in some instances exhibiting a distinctive knobbly surface and associated (rarely) with near vertical burrows 4-6 cm in diameter and up to one metre in length, belong to the ichnogenus *Ophiomorpha* (Häntzschel 1975, Frey and Howard 1970). *Ophiomorpha* is confined to the coarse sandy Kaihoka Member. The characteristic knobbly appearance is observed where burrows are mud lined, or where burrows project into underlying muddy fine sandstone Te Hapu Member lithologies. Generally, only the anastomosing part of the burrow is present; vertical tubes of the upper part of the burrow complex are only found locally at the Abel Head section (Fig. 3.14).

In recent environments *Ophiomorpha* burrows are formed by the genus *Callianassa* in littoral and sublittoral environments (Weimer and Hoyt 1964).

Type A ichnogenus resembling *Planolites* (Fig. 3.15)

Sinuous to straight tubes of 2-3 mm diameter, commonly parallel but sometimes perpendicular or oblique to bedding, resemble the ichnogenus *Planolites* (Häntzschel 1975). Two taxonomic types with otherwise identical features are included within the Type A ichnogenus. Tubes occur as endichnial muddy infillings in the Te Hapu Member muddy fine sandstones (Fig. 3.15) or as exichnial, very fine sand and silt infillings in the Te Hapu and Turimawiwi mudstones and siltstones (Fig. 3.15). The Type A ichnogenus is interpreted as a feeding trace.

Type B ichnogenus resembling *Arthrophycus* (Fig. 3.16)

Exichnial, vertical, horizontal and oblique, straight to slightly curved subcylindrical tubes 1-2 cm diameter, with meniscus structures and occasional bifurcation (Fig. 3.16), resemble the ichnogenus *Arthrophycus*. In the Rakopi Member, meniscus structures composed of alternate concentrations of glauconite and carbonate mud are characteristic. In the Paturau Member, dense concentrations of burrows with similar morphology but with no textural or compositional contrasts within and beyond the burrow, and revealed only by exceptional weathering, probably belong to the ichnogenus *Arthrophycus*. Burrows are interpreted as fodinichnia.

Type C ichnogenus. Large tubes.

Simple, exichnial, sand infilled, vertical, oblique and horizontal tubes 1-2 cm diameter in muddy Te Hapu or Turimawiwi Member lithologies are interpreted as domichnia.

Type D ichnogenus resembling *Keckia* (Fig. 3.17)

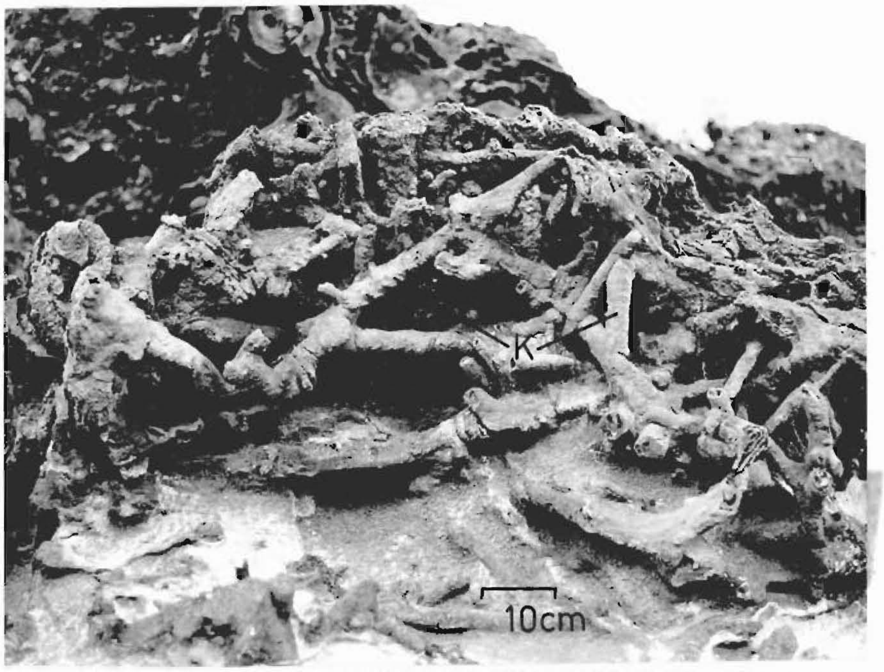
Endichnial, straight to slightly curved traces 6-8 mm wide, with curved muddy annulations parallel to bedding (Fig. 3.17), resemble the ichnogenus *Keckia* (Häntzschel 1975). Type D ichnogenus is restricted to the Te Hapu Member and is interpreted as a feeding trace.

Type E ichnogenus. Small tubes (Fig. 3.18)

Simple, straight, vertical, oblique and horizontal silt infilled tubes 5-7 mm diameter, were recorded in alternating siltstones and fine sandstones in the North Cape Formation at one locality.

Type ~~E~~ F ichnogenus. Large tubes (Fig. 3.19)

Simple vertical tubes, 2-3 cm in diameter and 6-7 cm long, were recorded at one locality in the North Cape Formation. The tubes are interpreted as dwelling traces; sand has infilled burrows occurring in a dark siltstone lithology. Horizontal burrows of similar diameter are associated with the vertical tube structures.

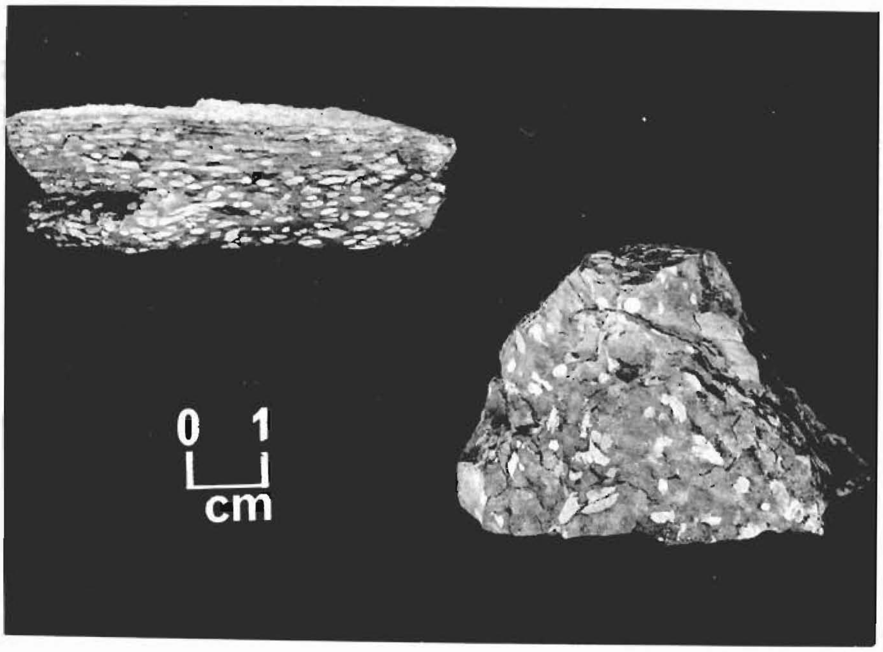


a) Anastomosing *Ophiomorpha* burrows, with characteristic knobbly tubes (K) in massive coarse sandstone, Kaihoka Member. Printed from colour slide.

b) Vertical tubes (V) part of *Ophiomorpha* burrow in massive coarse sandstone, Kaihoka Member. Hammer length is 32 cm. Printed from colour slide.

Fig. 3.14 *Ophiomorpha* burrows, Kaihoka Member.

a) Simple winding muddy burrows in fine sandstone, Te Hapu Member. Pen length is 15 cm.



b) Simple, winding silty burrows parallel to bedding in mudstone, Te Hapu Member, viewed perpendicular (top left) and parallel (bottom right) to bedding. Photo by A. Downing.

Fig. 3.15 Type A ichnogenus resembling *Planolites*.

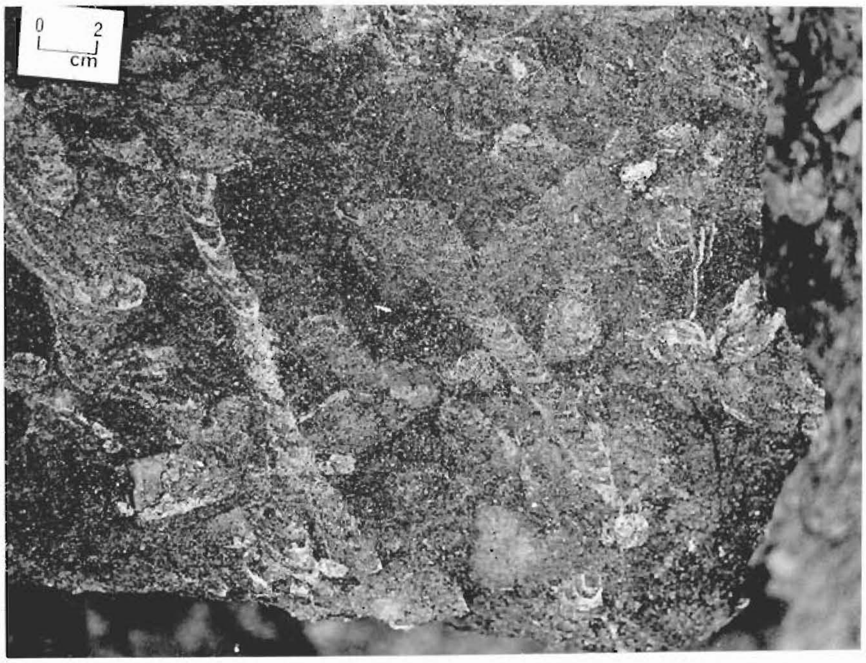


Fig. 3.16 Type B ichnogenus resembling *Arthrophycus*, with straight to slightly curved tubes exhibiting meniscus structures, Rakopi Member. Scale is 2 cm.

Fig. 3.17 Type D ichnogenus resembling *Keckia*, straight to slight curved traces, Te Hapu Member. Coin diameter is 3 cm.

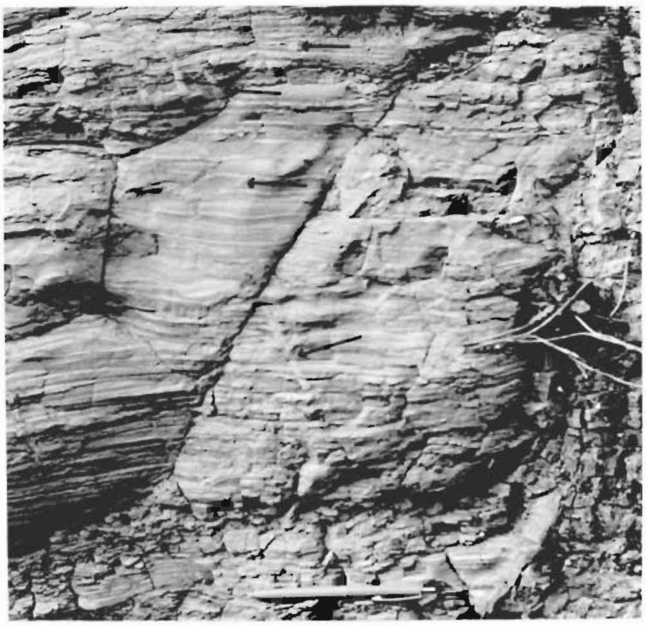


Fig. 3.18 Type E ichnogenus with straight, silt infilled tubes (indicated by arrows) in alternating silstone - fine sandstones, North Cape Formation. Length of pen is 13 cm. Printed from colour slide.

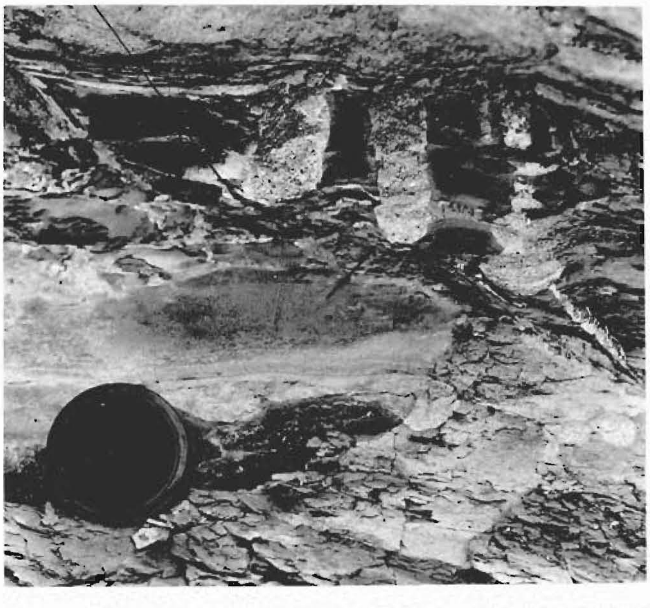


Fig. 3.19 Type F ichnogenus with sand filled vertical tubes in dark siltstones, North Cape Formation. Lense cap diameter is 5.5 cm.

CHAPTER IV

COMPOSITION AND DIAGENESIS

CONGLOMERATES

Table 4.1 shows clast variety within the lower Abel Head Formation and Pakawau Group. In the lower Farewell Formation (Wharariki Beach), predominant clast lithologies are quartz sandstone and quartz vein types. Granite, gneiss, volcanic and minor amounts of schist and subschist, comprise the remainder of clast lithologies. The Pakawau Group exhibits an upward increase in the degree of weathering of clasts, and a decrease in the proportion of granite and volcanic pebbles. Abel Head Formation conglomerates consist entirely of quartz sandstone and quartz vein clasts.

SANDSTONES

Arenaceous sediments of the Pakawau Group and lower Abel Head Formation are plotted on a ternary Q-F-R diagram in Fig. 4.1. Staining techniques (Bailey and Stevens 1960, Hayes and Klugman 1960) enabled estimation of feldspar percentages. Feldspar and rock fragment content, and ratios between Q-F-R and matrix-other components, were determined by point counting for all plotted samples. Sandstones of the Pakawau Group and lower Abel Head Formation plot within the feldsarenite and subfeldsarenite fields; several samples

PEBBLE COMPOSITION ANALYSIS OF LOWER FAREWELL FORMATION*		VISUAL COMPARISON OF LOWER FAREWELL FORMATION WITH OTHER FORMATIONS, MEMBERS	MEMBERS, FORMATION
Type	%		
Quartzose sandstones, minor chert, dark argillites.	56	Entirely quartzose sandstone and quartz vein pebbles	Kaihoka Tē Hapu Nguroa
Granite, gneissic granite (mostly weathered)	20	Decrease in proportion of granitic and volcanic pebbles, weathering of these more extensive than L. Farewell Fm. Locally (Kaihoka), high proportions of quartzose sandstone and quartz vein types.	Upper Farewell Formation
Volcanic (weathered)	10		
Schist, semischist	2		Lower Farewell Formation
Quartz vein	12	Fresh granitic pebbles.	North Cape Formation

(* see appendix)

Table 4.1. Stratigraphic Variation of Conglomerate Composition, Pakawau Group and Lower Abel Head Formation.

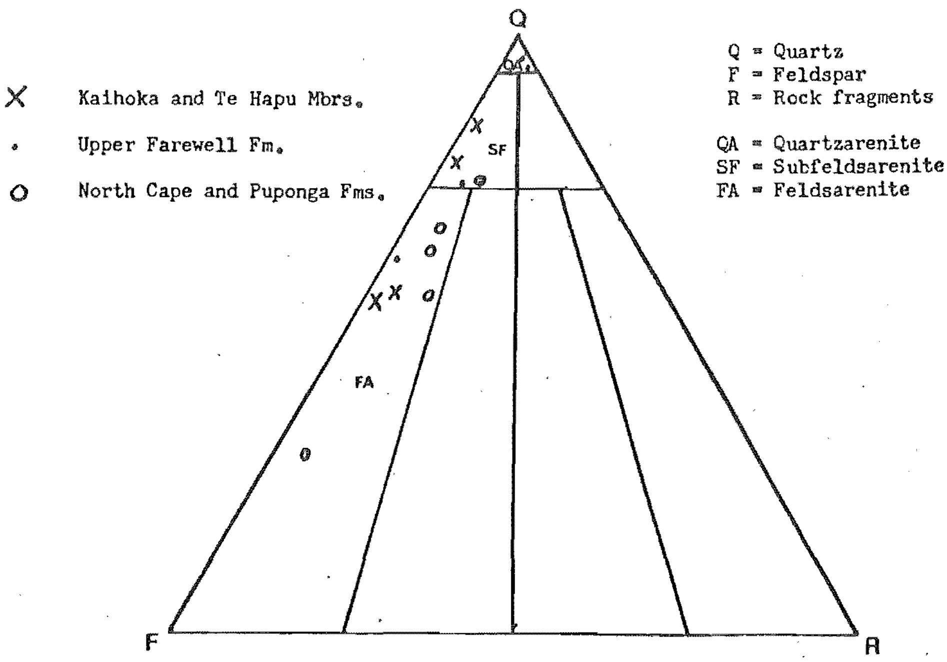


Fig. 4.1. Q-F-R diagram of Pakawau Group and Lower Abel Head Formation sandstones (feldsarenite, subfeldsarenite and quartzarenite fields based on Folk et al. 1973).

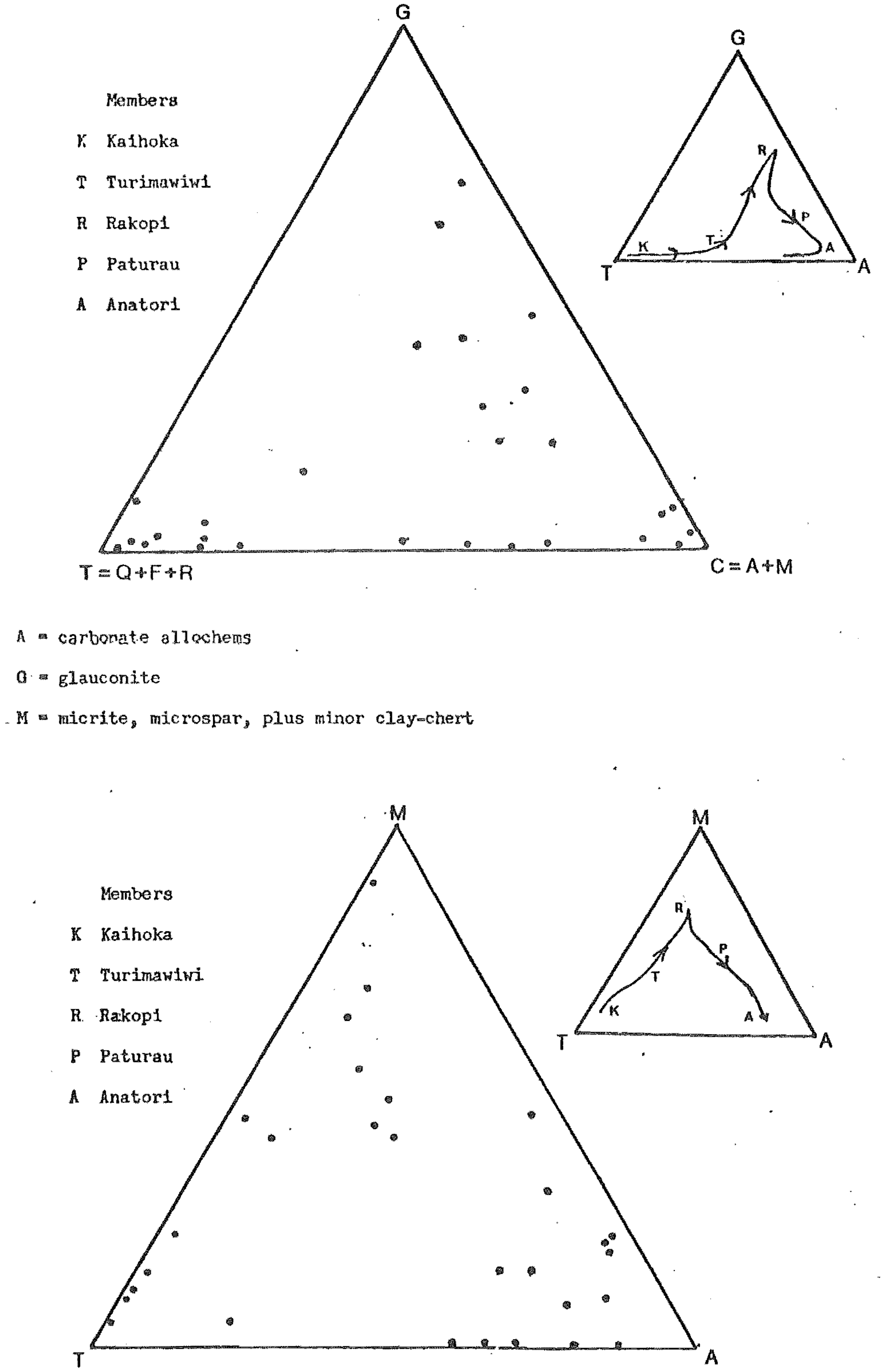


Fig. 4.2. T-M-A and T-G-C plots for Abel Head Formation and Takaka Limestone lithologies.

from the upper Farewell Formation are quartzarenites. Feldsarenites in the Pakawau Group generally have a high biotite content (trace - 16%); in subfeldsarenites and quartzarenites, mica (muscovite) comprises less than 1%. In the upper Farewell Formation (Kaihoka Section), quartzarenite is associated with quartzose conglomerates, and kaolinized and chertified sandstone matrix and volcanic clasts.

Variation in carbonate, glauconite and detrital content in the Abel Head Formation and Takaka Limestone is plotted in the ternary T-M-A and T-G-C diagrams of Fig. 4.2.

Members of the Abel Head Formation and Takaka Limestone exhibit an upward compositional change from arenaceous (Kaihoka, Te Hapu, Turimawiwi Members), to glauconitic and micritic (Rakopi Member), and to allochemical carbonate lithologies with subordinate detrital components (Paturau and Anatori Members). The Anatori Member locally contains 35-40% detrital sand (Q : F : R estimate = 15 : 2 : 1)

Quartz

Quartz is ubiquitous; variation in its abundance in the Pakawau Group and lower Abel Head Formation is illustrated in Fig. 4.1. Quartz content of the Rakopi Member and the Takaka Limestone (glaucarenites and calcarenites, not included in Fig. 4.1) ranges from a few per cent to 35%.

Monocrystalline quartz, often with undulose extinction, and polycrystalline quartz, with sutured intercrystalline boundaries and undulose extinction (plutonic quartz), comprise 95% of quartz in the Kaihoka Member coarse sandstones. The remaining 5% of quartz types comprise subequal proportions of polycrystalline recrystallized metamorphic (internal grains are subsequent and have straight boundaries), stretched metamorphic (internal grains are elongate) and gneissic types (internal grains are elongate, have sutured intercrystalline boundaries and exhibit biomodal size distribution).

Feldspar

Feldspar abundance is illustrated in the Q-F-R diagram of Fig. 4.1. Refractive index, 2V, twinning properties and staining, indicate orthoclase and microcline are the most abundant types, with albite and sodic oligoclase comprising less than 5% of total feldspar.

Generally, feldspars exhibit a similar size range to quartz. Fine sandstones of the lower Abel Head Formation and the upper North Cape Formation exhibit higher feldspar content that coarse sandstones of the same formations.

Vacuolization of feldspar and alteration to sericite ranges from slight alteration along cleavages, to extensive in which the original variety cannot be determined. Feldspars of Abel Head Formation and Anatori Member lithologies show only slight alteration. Feldspars in Pakawau Group lithologies range from fresh to extremely altered, and each of the species microcline, orthoclase and albite exhibits a range in degree of alteration; the proportion and extent of alteration is generally greater in coarse sand to granule size lithologies.

Rock fragments

Rock fragments comprise a maximum of 10% of detrital components in lower Abel Head and Pakawau Group lithologies (Fig. 4.1). Rock fragments within the upper Farewell Formation and the Kaihoka Member consist entirely of muddy and fine-medium quartzarenite lithologies and minor chert. In the Pakawau Group, micaceous and cherty argillaceous and semischistose rock fragments predominate; quartzarenite and chert fragments are subordinate, and volcanic rock fragments are extremely rare. Probable source rocks are the Paleozoic Haupiri and Aorere Group sandstones, argillites, slates and subschists which now outcrop throughout the Golden Bay area.

Micas

Generally, Pakawau Group sandstones consist of a trace to 16% mica. Locally in the North Cape Formation, fine sandstones up to one metre thick consist of up to 40% biotite (thin section estimate of sample sectioned perpendicular to bedding); commonly, mica exhibits high concentration in thin fine sandy siltstone drapes.
The high proportion of micas in finer lithologies reflects hydrodynamic control (see Folk 1968). In the North Cape Formation feldsarenites, the biotite : muscovite ratio is 8:1. In the upper Farewell Formation quartzarenites (Kaihoka Section), micas consist entirely of muscovite and constitute less than 1% of detritus.

Biotite (and alteration products) were estimated as comprising 15% of a Te Hapu Member muddy fine sandstone, and 16% of a Kaihoka Member fine sandstone. In the Te Hapu Member, biotite exhibits alteration to a pale brown variety ("leached biotite", Folk 1968), green biotite and chlorite. Separation of lamellae, due to swelling during hydration, occurs in Te Hapu and Pakawau Group lithologies. Biotite occurs as rare flakes with partial alteration to vermicular glauconite in the Rakopi Member. Muscovite occurs in trace amounts in Abel Head Formation and Takaka Limestone lithologies.

Heavy minerals

Heavy minerals were identified in thin section and heavy mineral separates. Predominant heavy minerals in approximate order of abundance are zircon, magnetite, sphene and epidote. Subordinate heavy mineral species include garnet, rutile, apatite, chlorite, tourmaline and ilmenite-leucoxene. Heavy minerals comprise less than 1% of Pakawau Group and Abel Head Formation lithologies, with the exception of Kaihoka Member well sorted fine sandstones which locally contain up to 15% heavy minerals, mostly magnetite-ilmenite. Many heavy mineral grains retain euhedral-subhedral form, others are angular to subrounded. Grains range from fresh to altered; zircons in the upper Farewell Formation exhibit corrosion and alteration around margins. Lateral and vertical changes in composition and morphologic variation await further investigation.

Authigenic sphene, consisting of slightly disseminated clusters of euhedral rhombs, was identified in one sample from the North Cape Formation.

Matrix, Cement

The matrix/cement of Pakawau Group lithologies is predominantly replacement chert, with remnant clayey micaceous minerals and minor void filling chert. Secondary pedological matrix features are described under Pedogenesis. The Te Hapu and Turimawiwi Members have a cherty-clay matrix and void filling chert or chlorite. Matrix/cement of Kaihoka Member lithologies ranges from clayey with subordinate chert, to microsparite plus minor chert. Locally, microsparite has recrystallized to sparite, calcite has replaced an original clay-chert matrix or feldspar (Fig. 4.6), and the replacement reaction has produced ragged edges around detrital quartz. Matrix of Abel Head Formation lithologies contains a varying proportion of authigenic siderite (see Siderite).

GREENSANDS AND GLAUCONITE

Glauconite comprises 20-70% of the Rakopi Member. The Kaihoka, Turimawiwi, Paturau and Anatori Members contain relatively minor amounts of glauconite. The abundance of glauconite, textural relationships between glauconite and detrital and carbonate components, and distribution of glauconite morphologic types, is summarized in Table 4.2.

Lobate-mamillate types occur in highly glauconitic lithologies (60-70% Rakopi Member, 40% one horizon of the Kaihoka Member), are accompanied by micrite-microsparite, and commonly exhibit colour zonation features (Fig. 4.3). Colour-zoned glauconites have dark centres and pale edges comprising up to half the glauconite diameter. The boundary between dark and pale is sharp or gradational; some exhibit

Table 4.2 Glauconite characteristics

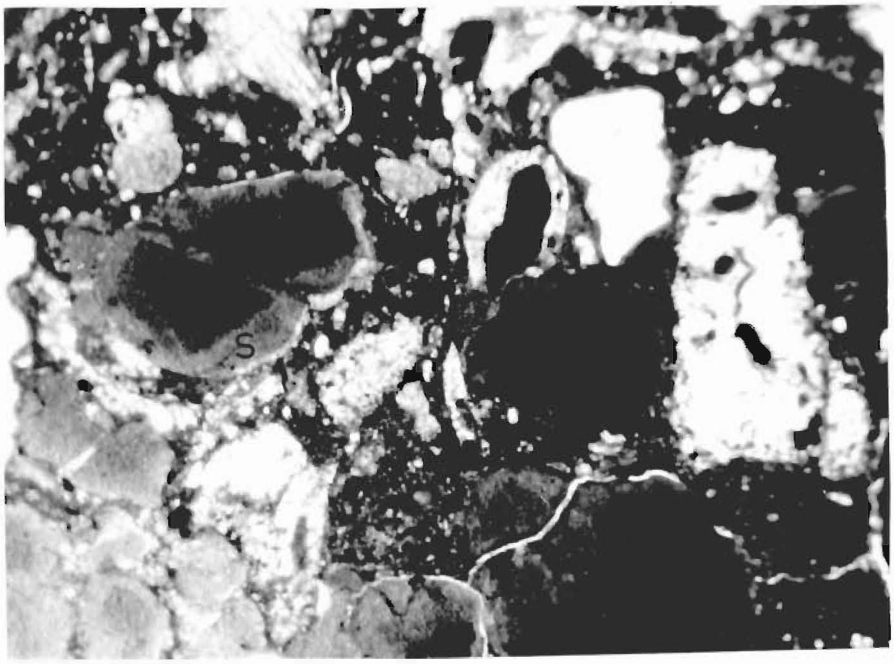
MEMBERS		% GLAUCONITE	GLAUCONITE CHARACTERISTICS	SALIENT GLAUCONITE-LITHOLOGY RELATIONSHIPS
ANATORI		0-5	Replacement and internal infilling of bryozoan, foraminiferal tests.	
PATURAU	Upper	trace	Replacement and internal infilling of bryozoan, foraminiferal tests.	
	Lower	0-20	Mostly spheroidal-ovoidal, occasional vermicular and lobate grains with colour zone features.	Spheroidal-ovoidal types similar size to carbonate allochems.
RAKOPI	Kahurangi	40	Mostly spheroidal-ovoidal, occasional vermicular and lobate gains with colour zone features.	Spheroidal-ovoidal types similar size to carbonate allochems.
	Abel Head Te Hapu (upper)	60-70	Lobate-mamillate types with colour zonation	Coarse sand size glauconite in biomicrites.
	Te Hapu (middle - lower)	20-40	Spheroidal-ovoidal and limonitized (middle)	Very fine-medium sand sized glauconites in coarse sandy foraminiferal biomicrite
KAIHOKA	Te Hapu (generally)	2-5	Spheroidal-ovoidal, vermicular and replacement.	Fine sand size glauconites in very coarse-coarse sandstone.
	Abel Head (1 horizon only)	40	Lobate-mamillate types with colour zonation.	Coarse sand size glauconite in muddy very coarse-coarse sandstone.

an additional thin outer perimeter or suture filling (in lobate types) of brown-green glauconite. Sharp contacts between colour zones and suture filling suggest episodes of glauconite accretion upon an originally formed nucleus (similar to others described by Bailey and Atherton 1969), rather than different maturation levels of glauconization (Ehlmann *et al.* 1963). Lobate-mamillate types exhibit desiccation or expansion cracks (MacRae 1972) containing pyrite framboids or a pale variety of glauconite. A complex history of lobate grain breakage, accretion and crack formation in the Rakopi Member is illustrated in Fig. 4.4.

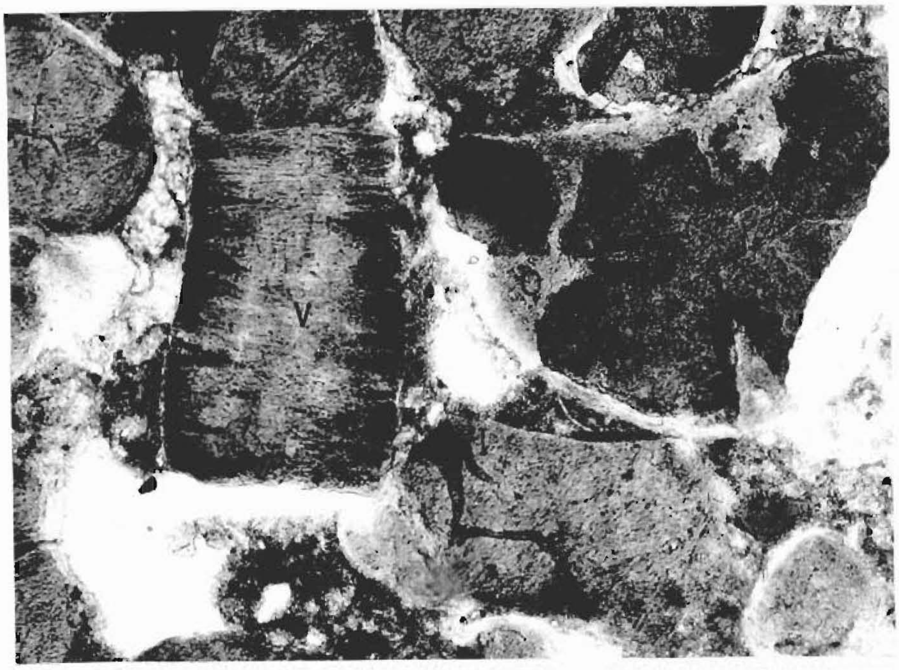
In the lower Rakopi Member (Sharks Head and Te Hapu Sections), fine sand sized spheroidal glauconites are associated with limonitized glauconites and rounded detrital coarse sand (Fig. 3.10d, cf. coarse sand size lobate-mamillate types Fig. 3.10c associated with high micrite matrix and low detrital sand content). In the Paturau and Kaihoka, spheroidal-ovoidal types are dominant and generally associated with a relatively low (2-20%) glauconite content (Table 4.2).

All glauconite lithologies contain a minor proportion of glauconite infilling foraminiferal and bryozoan chambers, and in rare instances replacing echinoderm and other shell fragments. In the upper Paturau and Anatori Members, nearly all glauconite is of an infilling or replacement type.

Limonitized glauconites (above) are interpreted as an ancient, rather than recent oxidation feature because half the total population of glauconite is fresh. Altered glauconites exhibit complete alteration or partial



a)



b)

Fig 4.3 Colour zoned and limonitized glauconites.

a) Glauconites with sharp (S) and gradational colour zoning(G). UC 7951.

b) Limonitized glauconite (L) with fresh glauconite overgrowth (O), vermicular glauconite and secondary glauconite infilling sutures(I) UC 7938.

In both figures plane polarized light and field of view is 2.25 mm.

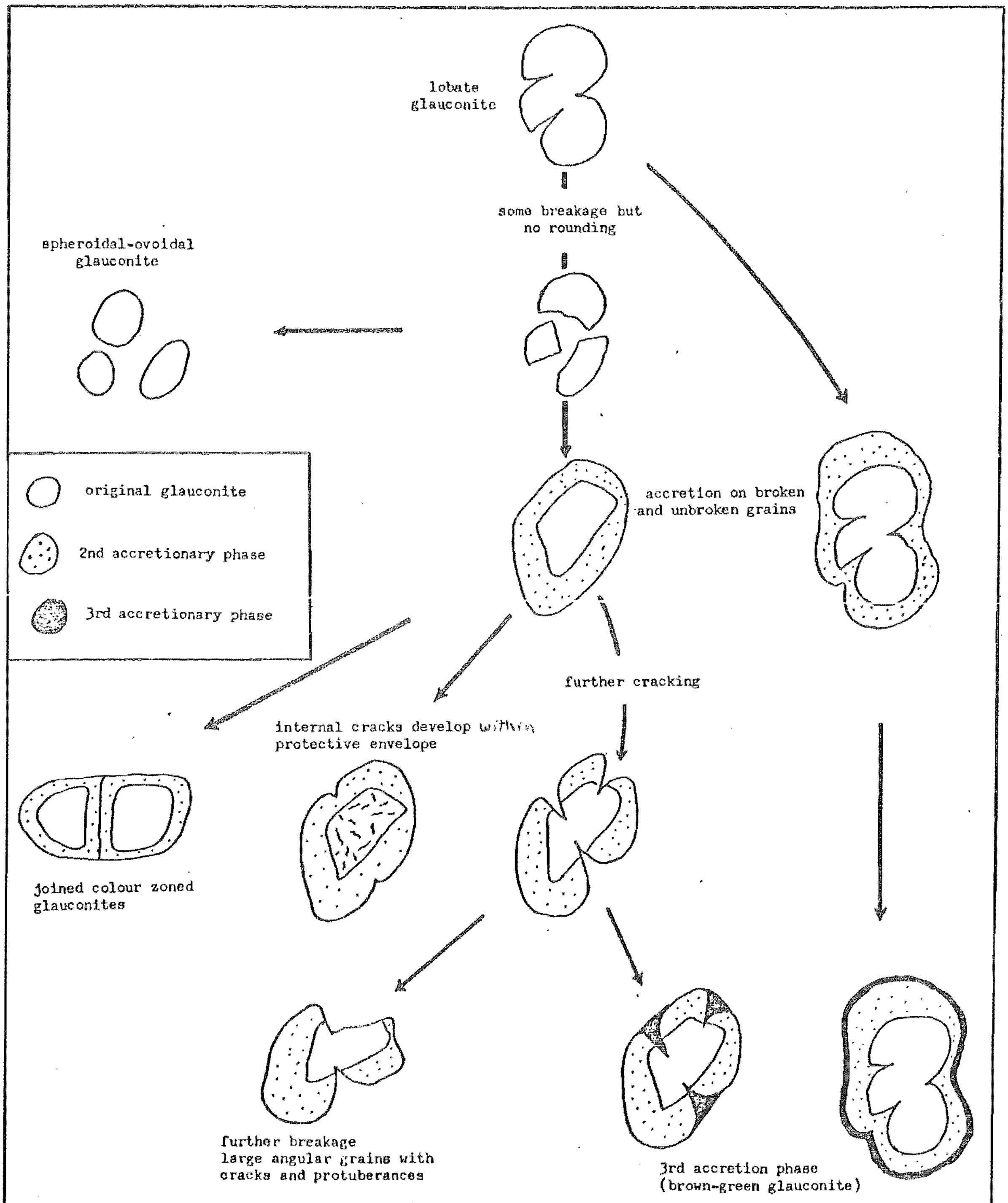


Fig. 4.4. Development of colour zonation and associated features in glauconites, Rakopi Member.

alteration around grain perimeters; some altered cores are surrounded by fresh glauconite (Fig. 4.14), and grains with an internal rim of alteration indicate a former glauconite diameter. Vermicular glauconite, and rarely biotite only partly altered to vermicular glauconite, is widespread in the Abel Head Formation, but forms only minor proportions of total glauconite (less than 1%).

Occasional inclusions occur in glauconites. Glauconites with sparse, very fine quartz sand or silt inclusions, reflect inheritance from an original or sandy clay aggregation subsequently transformed to glauconite. Rare inclusions of euhedral carbonate (siderite?), up to 30 μ size and surrounded by an unidentified fibrous mineral, have not been previously described; their significance is unknown.

LIMESTONES

The Paturau Member is a foraminiferal biomicrosparite. Near the base, the member is silty and glauconitic (UC 7945 Table 4.3); in its upper part and in interbeds in the middle and lower part of the member it is slightly silty (UC 7960 Table 4.3, Fig. 4.8). The Anatori Member ranges from sandy echinoderm-bryozoan foraminiferal biosparite to foraminiferal-echinoderm recrystallized biomicrite. Variation in allochem, detrital, matrix and cement content is illustrated in Table 4.3.

Echinoid spines and plates (Figs 4.10, 4.11) are present in all, and comprise up to 40% of Anatori Member lithologies, but only form minor proportions of the Paturau

Member (Table 4.3), although complete echinoderms are found therein. Foraminiferal tests (Figs 4.7, 4.8, 4.10, 4.11) constitute the major allochemical components of the Paturau Member and are generally secondary or minor components of the Anatori Member (Table 4.3). Benthonic foraminifera predominate in the Anatori Member, whilst planktonic foraminifera predominate in the Paturau Member. Bryozoan fragments (Figs 4.11, 3.12e) are common constituents of, and are restricted to, the Anatori Member (Table 4.3). Brachiopod and bivalve debris is a minor component of the Anatori Member, and large fragments or complete forms occur occasionally. Rhodoliths, up to a maximum diameter of 3 cm, are restricted to a micritic calcirudite in the Anatori Member (Kahurangi Section). The calcareous algae have grown on ovoidal clasts of micrite (Fig. 4.9). Elsewhere, rhodoliths and fragments are extremely rare or absent. Gastropods were not recognised in thin section, but rare intact forms with delicate ornamentation were found in the Paturau Member. Rare ostracods and chitino-phosphatic fragments occur in the Paturau Member. Coccoliths were recognised in thin section in micrite-microsparite and chert matrix at the base of the Paturau Member.

The proportion of detrital components varies from a few to 40% (Table 4.3). The Anatori Member contains a higher proportion of detrital components than the Paturau Member. Low proportions of detrital grains in both members are associated with increased proportions of micrite-microsparite.

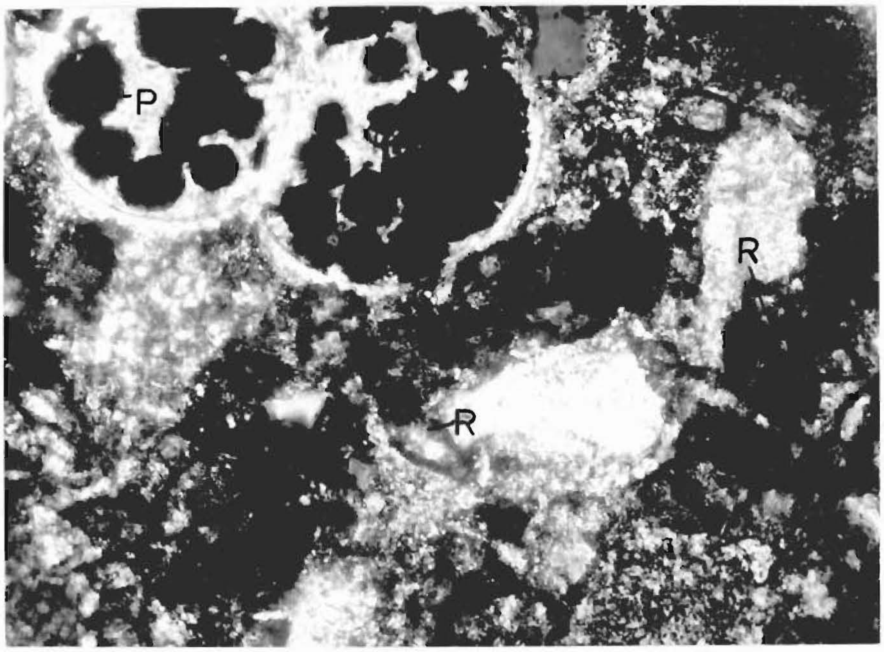


Fig. 4.5 Pyrite framboids (P) and sparry calcite in foraminiferal tests, siderite rhombs (R) in microspar and minor chert matrix, Rakopi Member. Plane polarized light. Field of view is 0.36 mm. UC 7950.

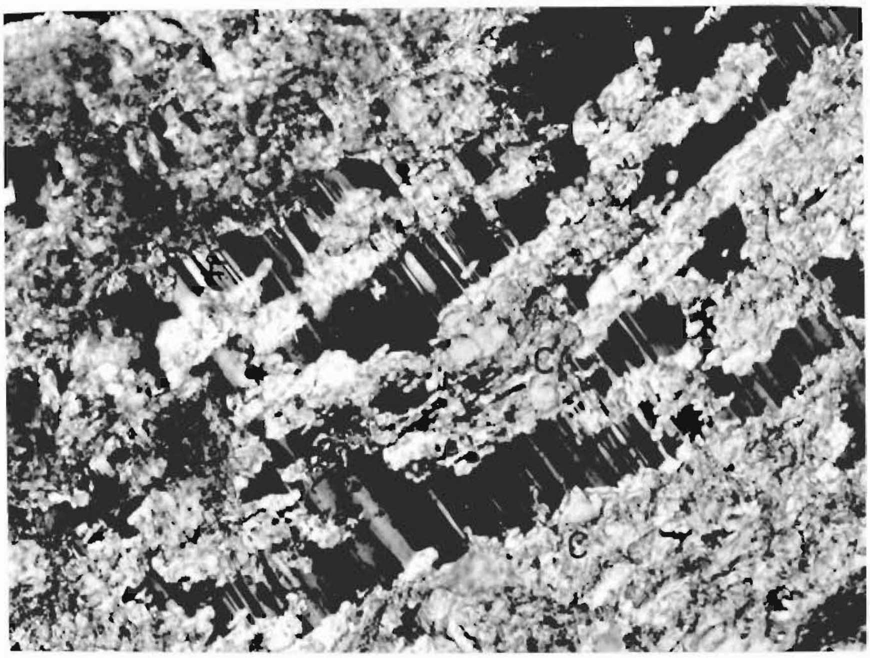


Fig. 4.6 Replacement of feldspar (F) by calcite (C), Te Hapu Member. Crossed polarizers. Field of view is 0.9 mm. UC 7942.

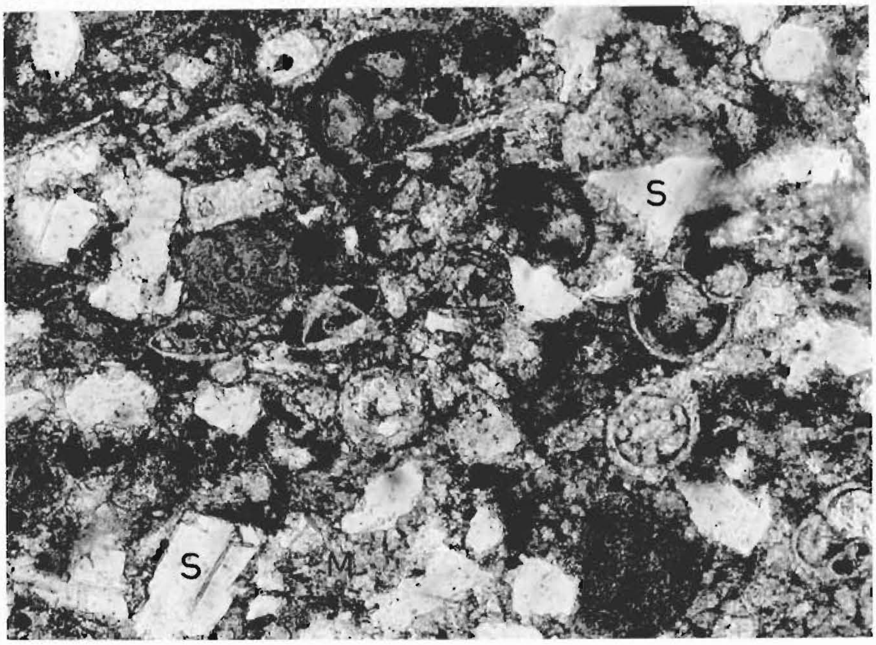


Fig. 4.7 Detrital silt - very fine sand (S), foraminifera, very fine size spheroidal-ovoidal glauconite (G) and sparite/microsparite (M), basal Paturau Member. Crossed polarizers. Field of view is 0.9 mm. UC 7945.

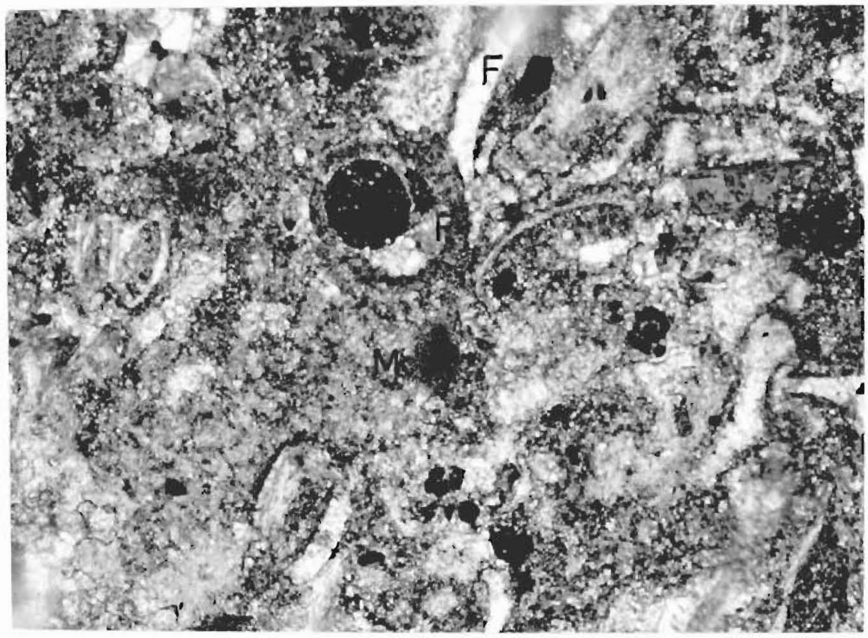


Fig. 4.8 Foraminifera (F) and micrite aggrading to microsparite (M) in micritic interbeds, Paturau Member. Plane polarized light. Field of view is 0.9 mm. UC 7960.

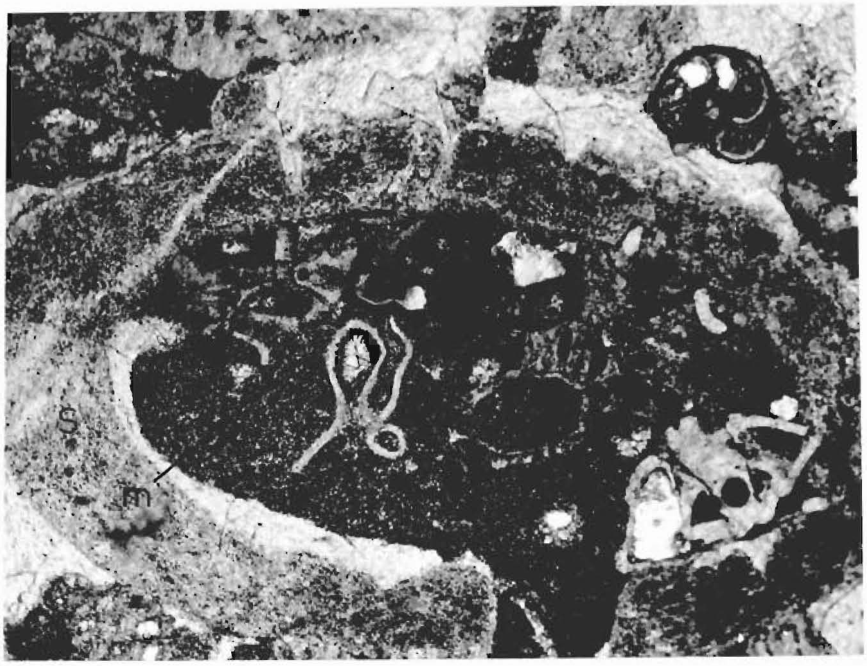


Fig. 4.9 Rhodolith consisting of calcareous algae grown on spheroidal clast of microspar and fine calcarenite allochems (m), locally replaced by sparry calcite (c), Anatori Member. Crossed polarizers. Field of view is 2.25 mm. UC 7978.

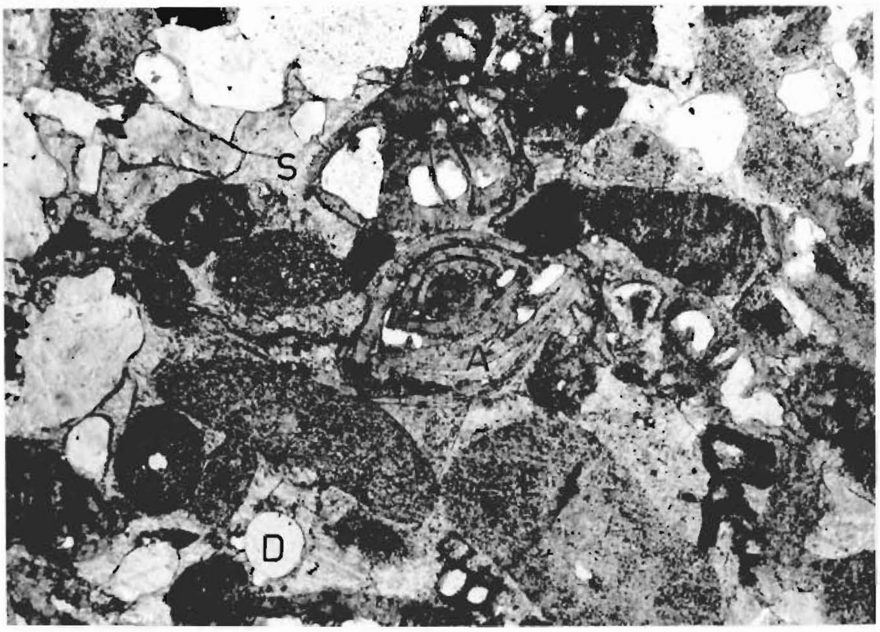


Fig. 4.10 *Amphistegina* (A), echinoderm fragments (E) with syntaxial rim cement, detrital quartz (D) and sparry cement(S), Anatori Member. Plane polarized light. Field of view is 2.25 mm. UC 7976.

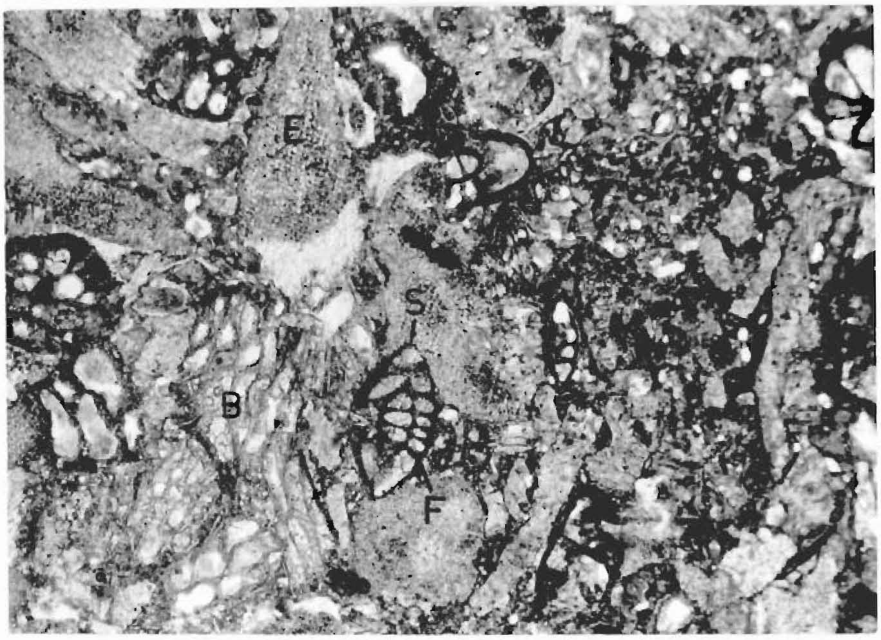


Fig. 4.11 Micritized foraminiferal tests (F), bryozoa (B), echinoderm plates (E) and stylolitic intergranular contacts (S), Anatori Member. Plane polarized light. Field of view is 2.25 mm. UC 7962.

Fig. 4.12 Remnant patches of micrite (M) aggrading to microsparite/sparite. Crossed polarizers. Field of view is 0.9 mm. UC 7979.

Table 4.3 Detrital and allochemical composition, and matrix, cement and diagenetic modification of Paturua and Anatori Members.

Member	UC No.	% detrital	Allochems in decreasing order of abundance	% matrix, cement	Matrix, cement diagenetic modification
Anatori	7917	12	B,E	31	S
	7976	35	E,F,B	30	S
	7977b	35	E,B	28	S
	7977a	40	E,B	20	S
	7978	5	E,B,F,R	20	M S
	7979	3	F,E	25	M MR S
	7963	15	E,P	10	ST, MR
	7962	5	E,B,F	10	ST, MR
	7921	20	E,F	20	S
Paturau	7919	10	F,E	30	MR, S
	7946	10	F	10	MR, S
	7960	5	F	45	MR
	7907	30	F	30	M MR S, CH
	7945	15	F(G)	15	MR, S

E - echinoderm
B - bryozoan
F - foraminifera
P - brachiopod, bivalves
R - rhodolith
(G) - glauconite

M - micrite
aggrading recrystallization
MR - microsparite
S - sparite
CH - chert
ST - stylolitization

Micrite, microsparite (formed by aggradational recrystallization of micrite, Figs 4.8, 4.12) and sparite (formed by open space precipitation or recrystallized micrite, Figs 3.12e, 4.9) constitute varying proportions of the Paturau and Anatori Members (Table 4.3). Minor amounts of clayey chert occur as irregular patches in micrite-microspar near the base of the Paturau Member (Fig. 4.5). Orthosparite cement, filling voids between allochems and foraminiferal and bryozoan chambers (Fig. 4.5), ranges from fine to very coarse. Syntaxial overgrowths on echinoderm fragments are mostly cement and rarely grain growth types. Locally, stylolitic contacts between adjacent allochems (Fig. 4.11), and pressure solution relationships between detrital quartz and adjacent carbonate allochems are developed. Micritization of foraminiferal tests is a common feature (Fig. 4.11).

PEDOGENESIS

The upper Farewell and Kahurangi Formations are characterized by kaolinization and silicification features.

In thin section, upper Farewell Formation lithologies exhibit a range of pedogenetic structures similar to those described by Brewer (1964) and Terrugi and Andreis (1970). Structures exhibit variety in relationship to surfaces, mineralogical nature and internal fabric. Kaolinites coating detrital grains (Fig. 4.13) are interpreted as grain cutans. Structures with irregular and concentrically lamellar fabric conforming with detrital grain perimeters (Fig. 4.15a) are interpreted as void cutans (Brewer 1964).

Straight or curved structures with internal lamellar fabric perpendicular to elongate sides, and exhibiting minor influence by detrital grains (Fig. 4.15b), are interpreted as channel cutans. Where internal fabric is not influenced by surface form, structures are interpreted as papules (Fig. 4.15c, a variety of glaebule, Brewer 1964). Cutans or papules with rounded features with the appearance of having disintegrated parallel to lamellar structure suggest reworking; alternatively, rounded ends of papules or cutans are sections of winding channels or pedotubules. Cutans range from simple forms composed entirely of chalcedony (chalcedans) to compound forms consisting of chalcedony and microcrystalline grains of several microns (probably kaolinite). Uniformly distributed microcrystalline grains impart a massive appearance to cutans, whilst concentration of microcrystalline grains imparts a lamellar appearance, often with undulose extinction (Fig. 4.15).

Siliceous nodules up to several centimetres in diameter, associated with vertical root structures (see Kahurangi section, back pocket), are interpreted as glaebules (Brewer 1964) and resemble 'pseudonodules' or syngenetic nodules described by Williamson (1951). Nodules consist of a predominantly cherty or opaline groundmass with minor vermiform kaolinite (100-400 μ), chalcedony and varied concentrations of microcrystalline kaolinite (Figs 4.16, 4.17). Concentrations of microcrystalline kaolinite (and locally pyrite) impart a contorted appearance to complex masses of chalcedans (Fig. 4.16), and resemble glaebules with convolute fabric (Brewer 1964) or 'colloform

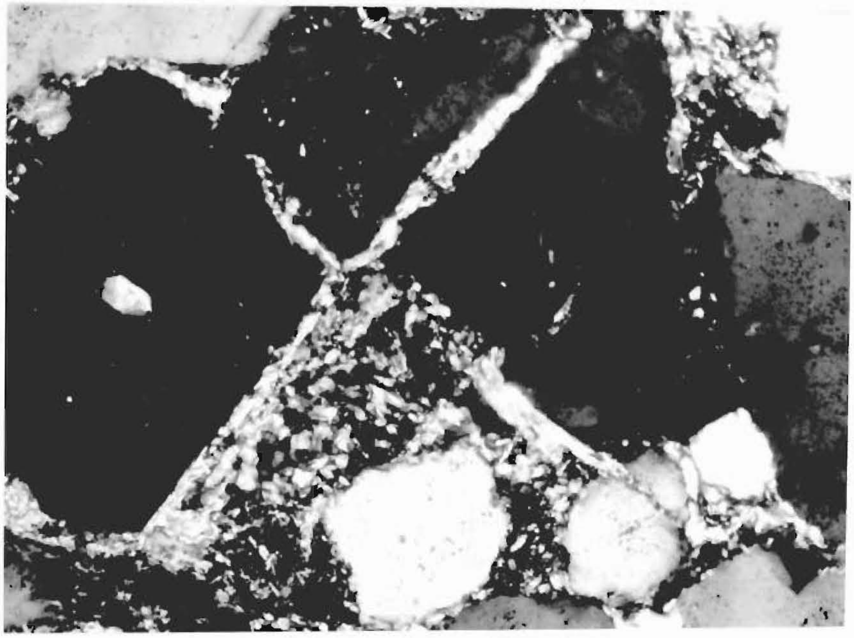


Fig. 4.13 Clay concentrations around detrital grains (grain cutans) in cherty clay matrix, upper Farewell Formation. Crossed polarizers. Field of view is 0.9 mm. UC 7929a.

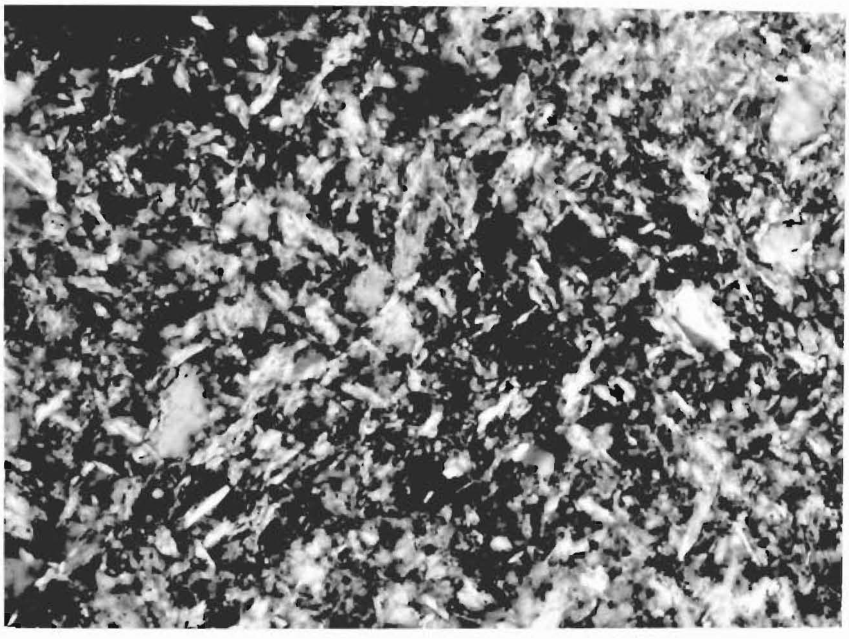
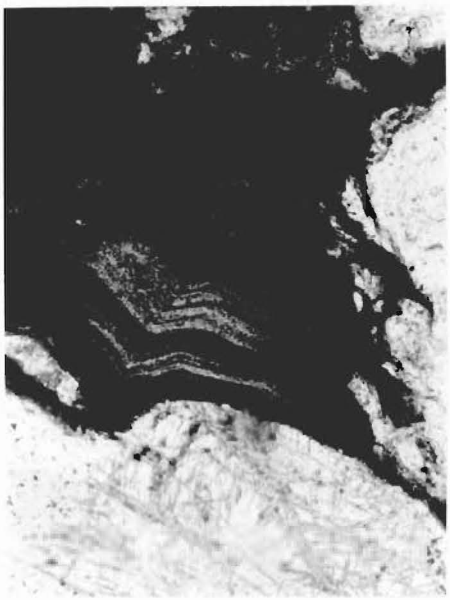


Fig. 4.14 Sepic fabric, upper Farewell Formation. Note preferred orientations of micaceous grains in silty cherty-clay matrix. Crossed polarizers. Field of view is 0.36 mm. UC 7988.



a) Void cutan, upper Farewell Formation. Note lamination conforming with void and detrital grain surfaces. Plane polarized light. Field of view is 0.62 mm. UC 7924.

b) Channel cutan, upper Farewell Formation. Note generally planar lamination, but conformity with detrital grain surfaces toward centre of photomicrograph. Plane polarized light. Field of view is 0.62 mm. UC 7927c.

c) Papule (reworked cutan?), upper Farewell Formation. Note lamination perpendicular to edges and undulose extinction in crossed polarizers. Field of view is 0.62 mm. UC 7927a.

Fig. 4.15 Void and channel cutans and papules, upper Farewell Formation

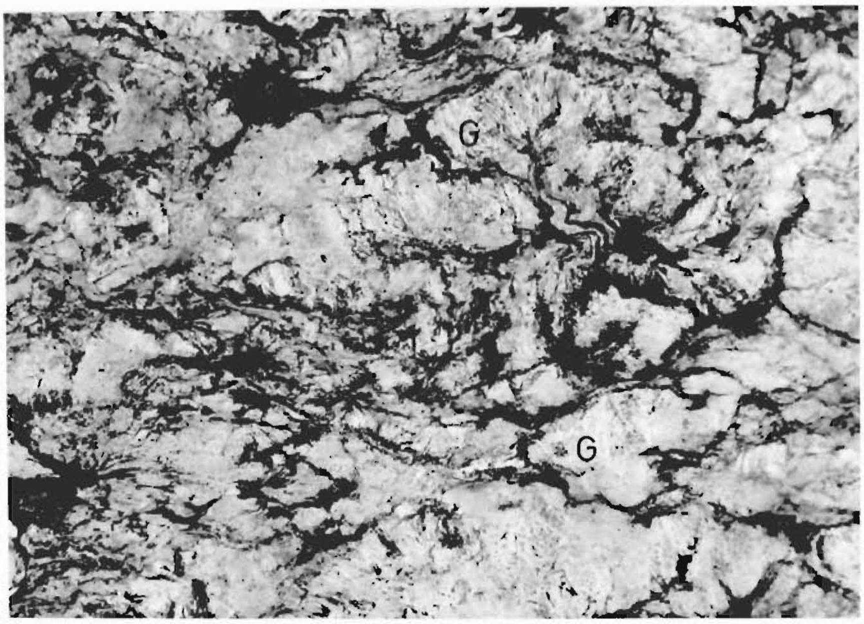


Fig. 4.16 Chalcedonic glaebule (chalcedony G) with convolute fabric. Dark areas are concentrations of microcrystalline kaolinite, occasional pyrite and limonitic stain. Kahurangi Formation. Crossed polarizers. Field of view is 0.9 mm. UC 7986.

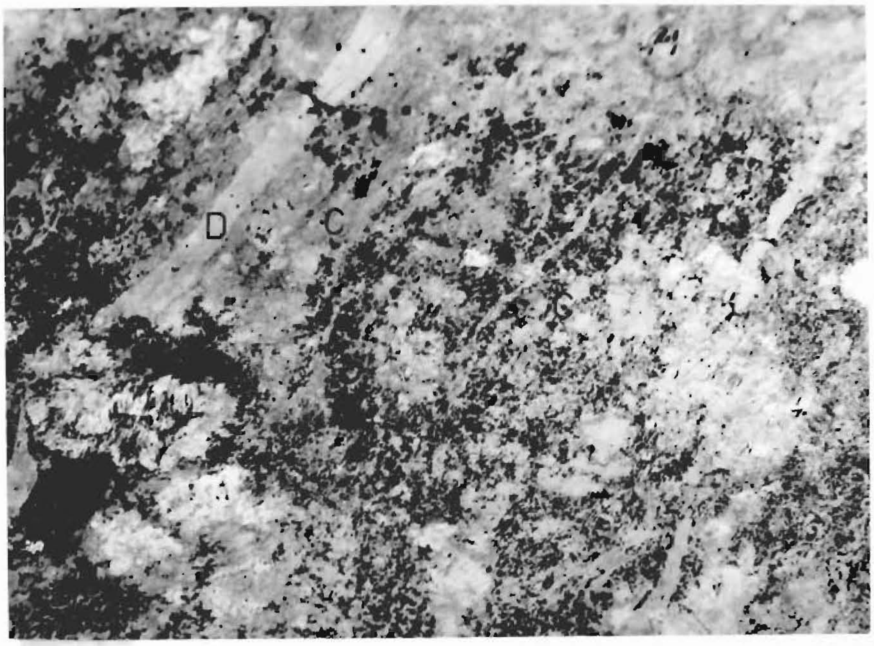
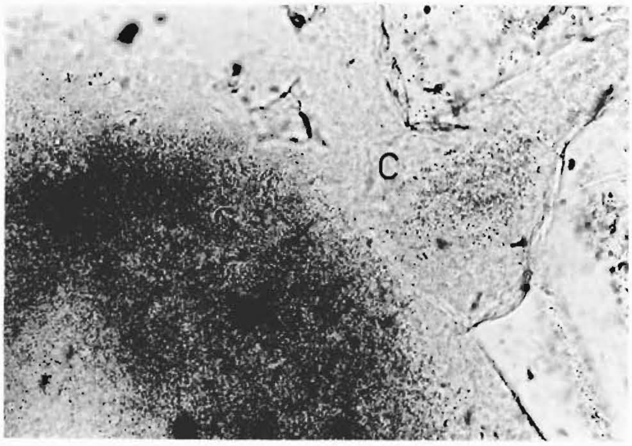
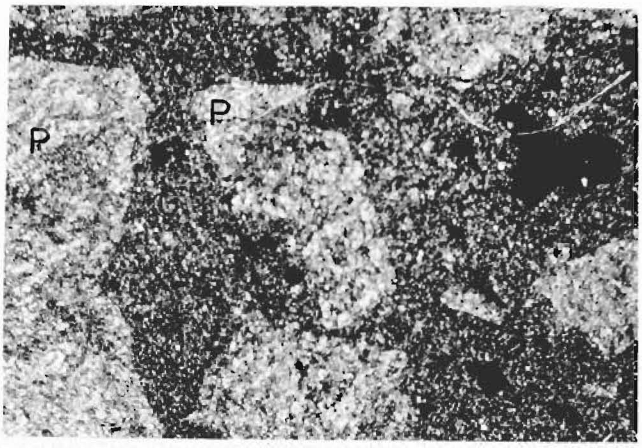


Fig. 4.17 Cherty opaline glaebule (C) cut by cherty dilation vein (D). Plane polarized light. Field of view is 0.9 mm. UC 7986.



a) Microcrystalline kaolinite (K) forming dense concentrations in clayey chert matrix (C). Plane polarized light. Field of view is 0.36 mm. UC 7987.



b) Vermiform kaolinite and chert pseudomorphing feldspar phenocrysts (P) and replacing groundmass (G) of volcanic pebble; upper Farewell Formation. Plane polarized light. Field of view is 0.36 mm. UC 7929.

Fig. 4.18 Kaolinization features, upper Farewell Formation structures' (Williamson 1951). Chert veins dissecting glaebules (Fig. 4.17) resemble dilation veins described by Williamson (1951). Microcrystalline kaolinite concentrations (Fig. 4.16) and chert veins are respectively interpreted as illuviation and void precipitation features developed subsequent to desiccation cracking (Brewer 1964, Williamson 1951).

Silicification of muddy lithologies is a characteristic feature of the upper Farewell Formation (Kaihoka, Te Hapu Sections) and the upper Puponga Formation (Whanganui Inlet). In the upper Farewell Formation, matrix is locally cherty with minor kaolinite exhibiting micaceous habit, or opaline-cherty with occasional chalcedonic masses. In both formations, chertification is accompanied by a sepic fabric development with micaceous kaolinite in a silty-cherty matrix exhibiting one or two preferred orientations (Fig. 4.14). Concentration of microcrystalline grains (? kaolinite) ranges from sparse to dense (Fig. 4.18a) and is interpreted as an illuviation feature concentrating plasma but unlike void cutans concentration has not been influenced by a specific surface.

In the upper Farewell Formation (Kaihoka Section), volcanic pebbles have been completely replaced by kaolinite and chert (Fig. 4.18b).

PYRITE-SIDERITE AUTHIGENESIS

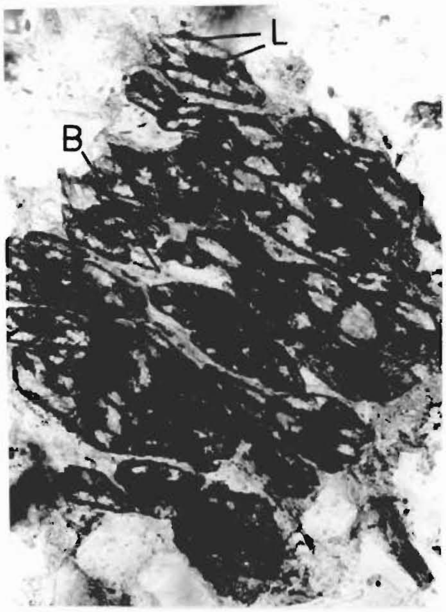
<u>Pyrite</u>

Pyrite is a common minor authigenic mineral in the Abel Head Formation and lower Paturau Member. It commonly occurs as framboids averaging 20 to 100 μ diameter in clayey matrix or microspar, within tests of small foraminifera (Fig. 4.5) and in glauconite between lobes and in internal cracks. In a coarse sandy lens with shell debris and mud clasts (Te Hapu Member), pyrite occurring as irregular elongate microcrystalline aggregates parallel to bedding is interpreted as pyritized carbonaceous material.

Siderite

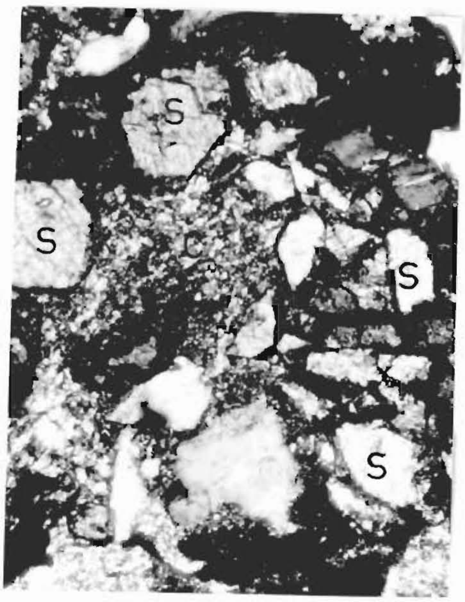
In the Farewell Formation, siderite occurs in rare spherical concretions up to 25 cm diameter as clusters of large crystals (up to 2 mm, Fig. 4.19).

In the Abel Head Formation, siderite is restricted to localities north of the Sharks Head Section. Euhedral siderite (rhombohedral or hexagonal in thin section) ranging from 20-160 μ (Figs 4.5, 4.19) generally comprises 2-20% of lithologies with clayey or microspar matrix. Locally in the Rakopi Member (Sharks Head and Te Hapu Sections) a distinctive one metre horizon contains up to 40% siderite. Alteration to limonite ranges from absent, to slight around crystal perimeters, to extensive. Where both siderite and pyrite are present, some siderite euhedra have pyritic centres (Fig. 4.19) indicating that siderite formation postdates pyrite formation. In the Kaihoka Member, subhedral-euhedral siderite forms a cement in spherical concretions (Te Hapu, Kaihoka Sections) or concretionary beds (Abel Head Section). Crystals are generally randomly orientated. In the Te Hapu Member, siderite is clustered along original mud laminations with high mica and matrix content. Siderite rhombs occur within altered biotite or



a) Euhedral siderite rhombohedra with two growth phases in altered biotite (B), Te Hapu Member. Siderite rims and initial growth phases altered to limonite (L). Note similar orientation of siderite crystals. Plane polarized light. Field of view is 0.62 mm. UC 7989.

b) Euhedral siderite rhombs with two growth phases (G) and pyrite nuclei (S) in cherty-clay matrix, Kaihoka Member. Plane polarized light. Field of view is 0.62 mm.



c) Euhedral siderite rhombohedra (S) in cherty matrix (C) in siderite concretions, Farewell Formation. Crossed polarizers. Field of view is 0.62 mm. UC 7990.

Fig. 4.19 Siderite characteristics

chlorite and are commonly elongate parallel to the cleavage plane of the enclosing mica (Fig. 4.19a). Siderite commonly exhibits evidence of two growth stages - the first indicated by siderite rhombs with a limonitized perimeter, the second as an enclosing siderite overgrowth in crystallographic continuity with the first (Figs 4.19a,b).

CHAPTER V

INTERPRETATION

FLUVIAL SEDIMENTATION PAKAWAU GROUP

General

Non-marine conditions after deposition are indicated by the presence of soil features and plant rootlets. Deposition of the Pakawau Group by fluvial processes is indicated by the similarities to lithofacies and structures described from recent fluvial environments. Considerable lateral and vertical variation in lithologies and lithological associations indicate wide variation in characteristics of the fluvial environments. Lateral coarse to fine changes represent either a response to increasing distance from source, or indicate that sediment was derived from locally adjacent source areas that supplied detritus of varying coarseness. Vertical changes represent response to potentially interrelated variables of climate, changing relief, position of shoreline relative to locus of deposition, and subsidence rates.

Three general fluvial associations have been proposed in a general model of fluvial sedimentation (Reineck and Singh 1975), namely: alluvial fan (mainly bedload), flood-plain (mixed bedload and suspension load) and coastal plain-deltaic (mainly suspension load). These may be laterally contiguous at any one time. Pakawau Group lithologies are included in the floodplain association which includes meandering braided stream and floodplain subenvironments.

Braided, meandering stream and floodplain sedimentary environments have a spectrum of diverse and overlapping characteristics, which depend on proximal-distal related characteristics of grain size, amount and variability of discharge, and stream sinuosity. The fundamental parameters of grain size, discharge and stream sinuosity determine the development of channel versus overbank sedimentation and the characteristics of channel sedimentation. Generally in meandering and braided streams, the results of channel and overbank sedimentation (suspension and finest bedload deposition) are distinct, whereas in floodplain deposits (muddy and sandy), channel and overbank deposits are indistinct. Meandering streams are finer grained and have a higher proportion of overbank sediments than braided streams (Miall 1977).

One approach to interpretation is to compare an ancient fluvial system with modern fluvial systems in which factors and processes determining sedimentation character are known and for which vertical profile models have been constructed. Fig. 5.1 reviews flow regime and bedform interpretation of the association of sedimentary structures and textures occurring in fluvial environments. Fig. 5.3 proposes a spectrum of fluvial environments based on the idealized models of Fig. 5.2, with which fluvial environments in the Pakawau Group are compared.

Meandering streams with stable discharge, broad shallow channels, low gradient and high sinuosity are characterized by cycles of laterally accreting point bar deposition and vertical accretion of sediments deposited from suspension on floodplains following overbank feeding. The lateral accretion process involves progradation of a point bar toward an actively migrating stream channel. An upward fining coarse sand (sometimes pebbly at base) to mud sequence is developed, and an erosional base is formed as the channel migrates laterally (Old Red Sandstone Type, Figures 5.2, 5.3, based on Allen 1970).

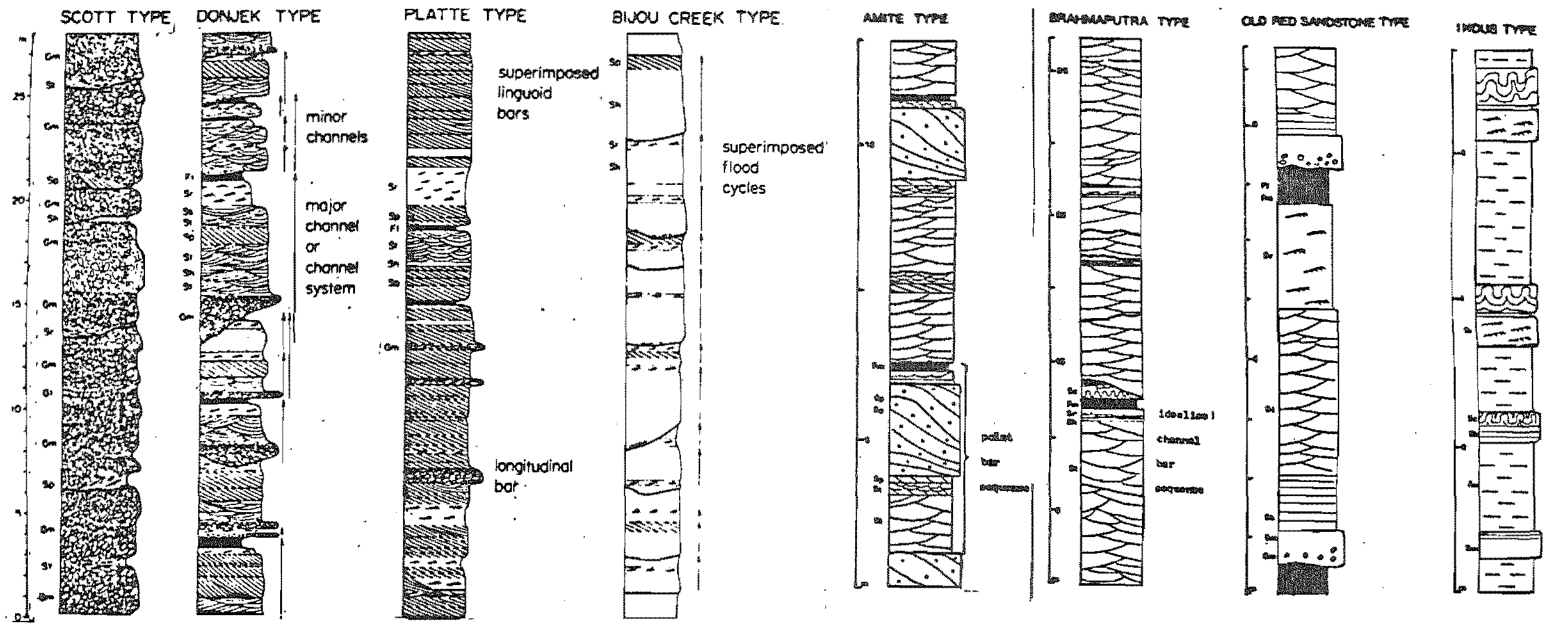
The braided stream depositional environment is diverse in characteristics. Channel filling is mainly by vertical accretion. Bars ("channel bars", Reineck and Singh 1975) form in midstream in response to declining competence, and migrate downstream (cf. point bar process of meandering stream). Maximum grain size, the range of associations of primary structure and textures, and the tendency for upward fining cycles are dependent on proximality to source, differentiation of topographic levels within the river environment, and variation in stream discharge. Vertical sequences reflect flood episodes, gradual channel filling, abandonment and reoccupation. The variety of braided stream types depicted in vertical profile models by Miall (1977) are included in Figs 5.2, 5.3.

Coarse grained lithologies (coarse sand-conglomerates) are generally associated with braiding and vertical accretion channel bar processes. Finer grained sediments, commonly associated with meandering deposition, may also be deposited by braiding and vertical accretion channel bar

Facies identifier for Fig 5.2	Lithofacies	Sedimentary structures	Interpretation
Gm	gravel, massive or crudely bedded, minor sand, silt or clay lenses	ripple marks, crossbeds in sand units, gravel imbrication	longitudinal bars, channel-lag deposits
Gt	gravel, stratified	broad, shallow trough crossbeds, imbrication	minor channel fills
Gp	gravel, stratified	planar crossbeds	linguoid bars or deltaic growths from older bar remnants
St	sand, medium to very coarse, may be pebbly	solitary or grouped crossbeds	dunes (lower flow regime)
Sp	sand, medium to very coarse, may be pebbly	solitary or grouped planar crossbeds	linguoid bars, sand waves (upper and lower flow regime), rapid upward shift in profile of equilibrium
Sr	sand, very fine to coarse	ripple marks of all types, including climbing ripples	ripples (lower flow regime)
Sm	granule conglomerate, to medium sandstone	massive	planar bed flow (lower and upper flow regime)
Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (lower and upper regime), gradual upward shift in profile of equilibrium
Sc	fine sand	convolute lamination, sandstone dykes	liquefaction
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours	minor channels or scour hollows
Fl	sand (very fine), silt, mud, interbedded	ripple marks, undulatory bedding, bioturbation, plant rootlets	deposits of waning floods, overbank deposits
Fm	mud, silt	rootlets, desiccation cracks, massive, parallel laminated	drape deposits formed in pools of standing water in abandoned channels or flood basin

Fig. 5.1 Review of interpretation of fluvial lithofacies (previously described in "Structures and Textures" and referred to in Fig. 5.2). Based on Miall (1977).

Scott
Donjek
Platte
Bijou Ck
similar
scale.



	SCOTT	DONJEK	PLATTE	BIJOU CK	AMITE	BRAHMAPUTRA	OLD RED SANDSTONE	INDUS
Major facies	Gm	Gm, St, Sr, Fl	Sp, St	Sh	Gp, Sp, St	St (large scale)	Sh, St, Sr	Fm
Minor facies	Gp, Gt, Sp, St	Gp, Sh, Ss,	Gm, Sh, Ss, Sr, Fm	Sr, Sp	Sh, Sr, Fm	Sh, Sr, Sc, Fm	Gm, Fm	Sr, Sm, Sc
Vertical profile	No major upward fining cycles. Small scale cycles Gm Sp, St, Sr	Major upward fining cycles due to channel aggradation, up to 35 m. Minor cycles Gm Sp, St, Sr, Fl	No major cycles Minor cycles Sp St	Sh Sr	Large scale cycles no data. Point bar cycles St St, Sp (small), Sp Gp, Fm. No upward fining	Large scale cycles no data. Channel bar sequence St (large), Sh Sr St, Fm, Sr Sc, Fm	Repeated upward fining cycles	Alternating mudstone, sandstone
General features	Proximal gravel rivers, may be ephemeral	Braided with marked differentiation of topographic levels, perennial or ephemeral	Topographic differentiation less marked, braided at low water, perennial or ephemeral	Ephemeral streams subject to catastrophic floods	Meander channels low water and straight channels during short duration floods	Distal low lying flood plain with high and variable discharge, braids, fine sediment	Successive migration of meandering streams across low lying floodplain	Distal, channel and overbank deposits indistinct

Fig. 5.2 General features, vertical profiles and facies assemblages of braided and meandering streams, and floodplain deposits (after Miall 1977; Allen 1965, 1970; Reineck and Singh 1973; McGowen and Garner 1970; and Coleman 1969).

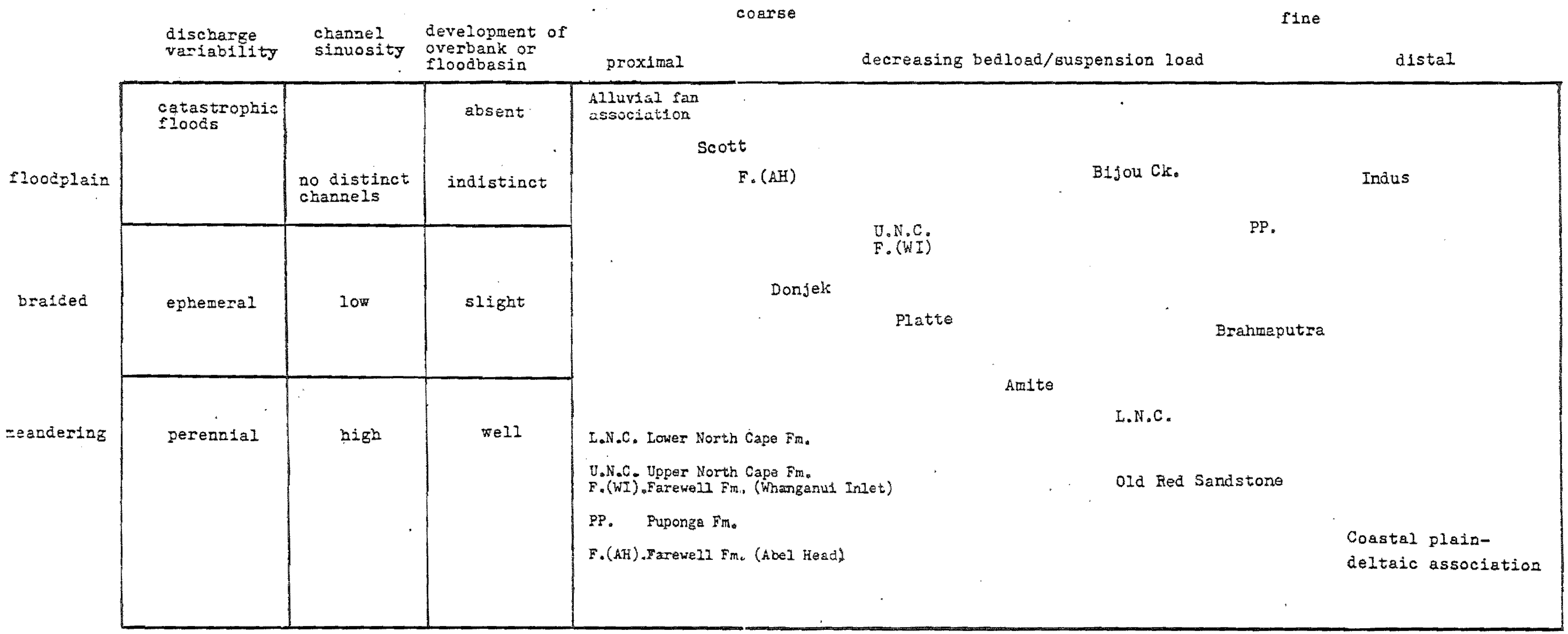


Fig. 5.3. Location of flood plain association vertical profile models in fluvial environment spectrum.

processes under conditions of periodic high discharge and sediment load, and deposits of either point or channel bars are indistinguishable (e.g. Brahmaputra Type, Figs 5.2, 5.3 based on Coleman 1969). The Amite Type (Figs 5.2, 5.3, based on McGowen and Garner 1970) is characterized by processes and lithologic characteristics intermediate between braided and meandering streams. The foregoing discussion and examples illustrate the difficulty or impossibility of distinguishing between fine grained 'braided' and 'meandering' stream deposits, and demonstrates the utility of interpreting fluvial lithologies as part of a braided-meandering spectrum.

In river systems without distinct flood basin and channel areas, sandy sediment is deposited during flood cycles. Sediments range from mixed bedload/suspension load deposits (e.g. Indus Type, Figs 5.2, 5.3, based on Reineck and Singh 1975, Allen 1965), to a distinctive association of predominantly horizontally stratified and climbing-ripple fine-medium sandstones (e.g. Bijou Creek Type, Figs 5.2, 5.3, based on McKee 1967).

The following analysis of the upper part of the Pakawau Group aims to assess the types of fluvial sedimentary environments by comparison with the spectrum of models, and to detect changes in character of fluvial sedimentation that are of interpretational significance in reconstructing the geological history of the area.

Braided stream and floodplain environments

The North Cape and Farewell Formations have the general characteristics of 'braided' stream deposits.

Several features are more indicative of braided rather than meandering stream deposition. Mudstone units of overbank or fine-grained channel-fill origin are thin relative to thick sandstone-conglomerate units. Conglomerates, often forming extensive sheets in the Abel Head-Puponga vicinity, have the characteristics of migrating longitudinal bars found only in braided streams. Channel structures of varying magnitude indicate accumulation via extensive scouring and subsequent filling - a characteristic more typical of braided stream deposition.

Lower and middle North Cape Formation (Whanganui Inlet): Description and interpretation of the lower North Cape Formation is outlined in Fig. 5.4. The lower and middle parts of the North Cape Formation are transitional in character. Alternating fine sandstone-mudstone lithologies, occasionally with coal or carbonaceous material, are commonly developed (e.g. sections at M25 676413, middle part of M25 693655, lower part of M25 693358, back pocket). Fine sandstone-mudstone lithologies exhibit thicker development than similar lithologies in the upper North Cape and Farewell Formations. In the lower North Cape Formation, channel-fill lithologies consist predominantly of horizontal or low angle cross-stratified sandstones, whilst the middle North Cape Formation also exhibits massive planar and cross-stratified granule conglomerate-very coarse sandstone (e.g. sections M25 713652, M25 641652, M25 687652, upper part of M25 693655, back pocket). One upward fining sequence similar to that depicted in Fig. 5.4 was observed;

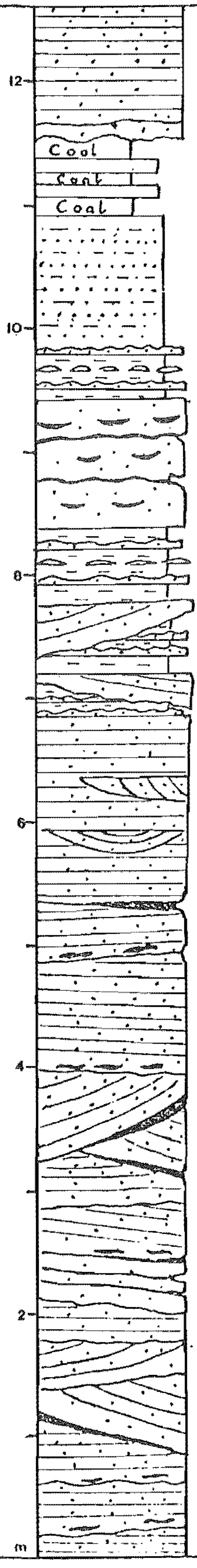
generally exposures are not sufficiently continuous to establish that progressive upward fining, rather than rapid change between channel and overbank sedimentation, is characteristic.

The lower North Cape Formation most closely approaches the meandering stream model in that it exhibits thick development of overbank deposits, including coal and carbonaceous mudstones, common development of fine alternating sandstone-mudstone types and a sequence with upward fining character.

Channel-fill sediments accumulated via a process of repeated scouring and formation of broad, shallow channels that were subsequently filled by plane bed sandstone deposits and thin siltstones during intermittent low water intervals. The process of scouring and filling and fluctuating flow conditions is considered more typical of braided stream deposition than the declining flow regime process of point bar migration, characteristic of the meandering stream model. Common, alternating fine sandstone-mudstones with minor sand-filled scours (middle part of Fig. 5.4) are interpreted as minor channel or overbank sediments accumulating away from the site of most active channel sedimentation, in areas subject to periodic channel reoccupation. The upward fining sequence is interpreted as representing progressive channel filling and transitional development to overbank sedimentation, as the site of most active channel sedimentation migrated.

The lower North Cape Formation represents a relatively fine-grained, braided stream environment with

Fig. 5.4. Generalised succession and interpretation of the lower North Cape Formation (Whangaui Inlet).



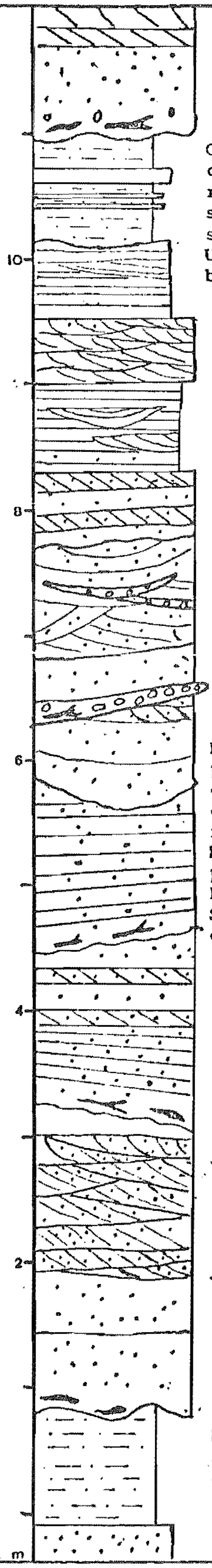
Description	Interpretation
Thin coals alternating with massive and carbonaceous siltstones.	Overbank gentle traction and suspension deposition and peat accumulation.
Alternation of thin fine sandstones and siltstones. Massive silt-fine sandstones often with carbonaceous material.	
Alternating medium-fine sandstones with small scale ripples. Occasional shallow scours and horizontally stratified sandstones.	Late stage channel-fill with periodic channel reoccupation, erosion and deposition.
Predominantly horizontal or low angle cross-stratified sandstones sometimes grading into medium and silty fine sandstone. Channel structures of varying scale with channel-fill cross-stratification. Occasionally channels lined by thin and often eroded silty fine sandstone. Occasional trough-fill cross-stratification. Erosional surfaces overlain by perigenic siltstone clasts. (At north end of Whanganui Inlet pebble-cobble lenses are interbedded in coarse sandstone facies.	Channel-fill deposition by planar bed movement and filling of scour channels. Varied flow suggested by silty fine sand lining channel bases or interbedded in horizontally stratified units.

common and often well developed overbank subenvironments. In a spectrum of fluvial environment models, the lower North Cape Formation occupies a position intermediate between the braided stream Platte Type and the meandering stream Old Red Sandstone Type (Figs 5.2, 5.3).

The middle North Cape Formation is intermediate in character between the upper and lower North Cape Formations. A probable lateral equivalent of the middle and lower North Cape Formations at the northern end of Whanganui Inlet, contains in addition to the associations described above, thin lensing pebble conglomerates that are interpreted as channel lag and channel bar deposits.

Upper North Cape Formation and Farewell Formation (Whanganui Inlet): The upper part of the North Cape and the Farewell Formation (Whanganui Inlet) can be characterized with one diagram (Fig. 5.5). Compared with the lower North Cape Formation, vertical sequences are characterized by thick sets of massive granule conglomerate-coarse sandstones, horizontal, planar and cross-stratified very coarse sandstones. Occasional thin conglomerate lags overlie scour surfaces. Thin lensoid units of overbank or channel-fill mudstones often overlie surfaces that are irregular and erosional. Siltstone drapes do not interbed with channel-fill sandstones or overlie channel scour surfaces as in the lower North Cape Formation. Increased and less varied flow conditions (cf. lower and middle North Cape Formation) are indicated by occasional pebble-cobble conglomerates, an increase in the proportion of granule conglomerates-very coarse sandstones, and the absence of

Fig. 5.5. Generalised succession and interpretation of the upper North Cape and Farewell Formations (Whanganui Inlet).

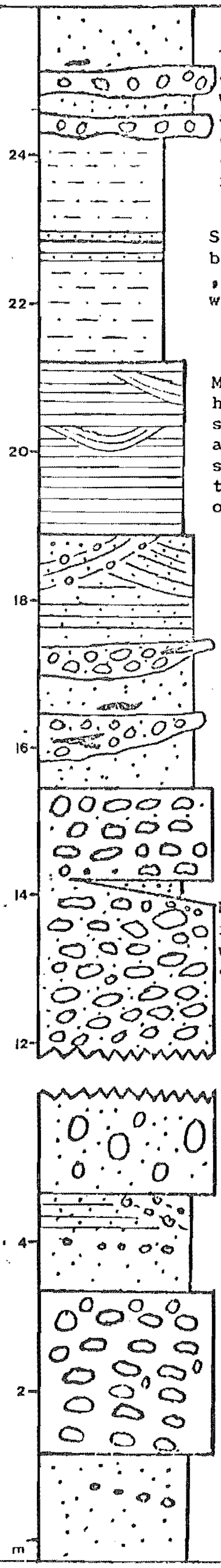


Description	Interpretation
Carbonaceous siltstone with occasional alternations of rippled lenticular fine sandstone and horizontally stratified medium sandstones. Unit often lensoid and basal contact irregular.	Abandoned channel gentle traction and suspension deposits with occasional incursion of medium sand.
Horizontally stratified, planar cross-stratified, channel-fill and trough cross-stratified and massive-very coarse sandstones. Massive granule and thin pebble conglomerates. Pebbles line channel scours. Small to large scale channels.	Repeated scouring and channel-filling by migration of linguoid and longitudinal bars, dune and planar bedforms.
Massive clayey siltstones, interbedded fine sandstones and siltstones.	Abandoned channel or overbank gentle traction and suspension deposits.

siltstone drapes in channel-fill sequences. Rapid shifts in the site of active channel sedimentation are suggested by the often sharp contact between coarse channel sediments and mudstones interpreted as abandoned channel-fill deposits. The upper North Cape and Farewell Formations resemble the Platte Type (Figs 5.2, 5.3) in that upward fining sequences are not developed, mudstone lithologies are minor, and planar cross-stratification is common. However, they differ in that horizontal, massive and channel fill cross-stratification, in the Upper North Cape and Farewell Formation, exhibits increased development. The upper North Cape and Farewell Formations are interpreted as a more proximal variant of the Platte Type. Smith (1970) notes that horizontal stratification, associated with longitudinal bar formation, increases in proportion upstream within the Platte River.

Farewell Formation (Abel Head): Description and interpretation of the Farewell Formation (Abel Head) is outlined in Fig. 5.6. The Farewell Formation is characterized by thick massive conglomerate, with thin, interbedded, massive or horizontally stratified sandstones. Alternating conglomerate and sandstone units are interpreted as longitudinal and linguoid bar, dune and planar bed flow deposits (see Fig. 5.1). Occasional upward fining sequences ranging from thick massive conglomerates to bedded sandstones and siltstones (Fig. 5.6) are interpreted as channel-fill sequences. Thin lensoid mudstone units are interpreted as abandoned channel fill deposits (similar to Whanganui Inlet lithotope). This association of features

Fig. 5.6. Generalised succession and interpretation of the Farewell Formation (Abel Head).

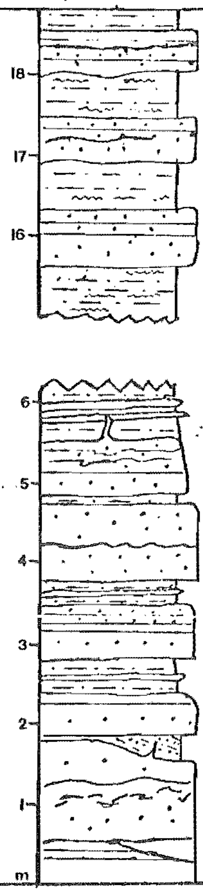


Description	Interpretation
Thin, irregular pebble conglomerates with carbonised wood stems, perigenic clasts, alternating with massive granule conglomerate-very coarse sandstone overlying irregular contact.	Erosion and return to channel deposition by advancing longitudinal bars and planar bedforms.
Siltstones with thin interbedded fine-coarse sandstones, massive clayey siltstones with carbonaceous remains.	Final stage channel-fill. Gentle traction deposits in abandoned channel.
Medium-coarse sandstones with horizontal stratification, small scale erosional troughs and channel-fill cross-stratification, defined by thin silty fine sandstone or mica concentrations.	Late stage channel-fill. Plane bed migration of medium-coarse sands, intervals of draping by micaceous or silty fine sands. Minor erosion and filling of scours.
Granular very coarse sandstone with horizontal, trough, planar and channel-fill cross-stratification, and massive granule conglomerate. Thin lenses of pebble conglomerate lining erosional scours. Conglomerate proportion decreases upward.	Channel-filling by advancing linguoid bars, dunes, planar bedforms, scour and fill. Lithologies fining upward in response to progressive channel filling.
Massive and poorly stratified sandy conglomerate with thin lenses of granule conlomerate-coarse sandstone.	Longitudinal bar deposits.
Massive conglomerate, sandstone, trough and channel fill cross-stratified granular coarse sandstone.	Repeated scouring and channel-filling by advancing longitudinal and linguoid bars and planar bedforms.

suggests that the Farewell Formation (Abel Head) was deposited under conditions intermediate between the Scott and Donjek Types of Miall (1977); see Figs 5.2, 5.3.

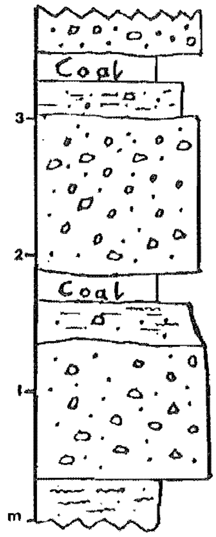
Puponga Formation (Whanganui Inlet): Description and interpretation of the Puponga Formation (Whanganui Inlet) is outlined in Fig. 5.7. Compared with the underlying North Cape Formation, the Puponga Formation is characterized by an increased proportion of siltstone lithologies, an absence of granule conglomerate-very coarse sandstones and pebble-cobble conglomerates. Furthermore, sandstone units are only of the order of one to several metres thick (cf. underlying North Cape Formation where sandstone units are of the order of ten to fifteen metres thick) and unlike the North Cape Formation, channel and overbank lithologies are not distinct. The proportion of siltstone units increases toward the top of the Formation (Fig. 5.7). The general association of clayey-siltstone lithologies, horizontal bedding and liquefaction features (Fig. 5.7) are common in fine-grained fluvial deposits with high sediment load, such as the upper parts of channel bars of the Brahmaputra River (Coleman 1969) or the Indus River (Reineck and Singh 1975). The lower Puponga Formation (Whanganui Inlet) is interpreted as representing a sandy floodplain environment with a high discharge of fine-medium sandy sediments; silty lithologies accumulated during waning current phases or between flood events. The upper Puponga Formation (Whanganui Inlet) is interpreted as a floodbasin environment accumulating clayey-silty sediments, with periodic crevasse splay deposition of fine-medium sandstone.

Fig. 5.7. Generalised succession and interpretation of the Puponga Formation (Whanganui Inlet).



Description	Interpretation
Alternating massive or laminated carbonaceous clayey siltstones and fine-medium sandstone units (similar below).	Silty floodplain sedimention with periodic crevasse splay or sheet sandstones deposited during flooding.
Sepic fabric. Silicification.	Soil formation. Silica release and deposition in response to wetting and drying near top of stable weathering profile.
Upward increase in proportion of siltstone units.	Lateral migration of channels supplying sand, or reduced supply of sand from hinterland.
Massive and horizontally stratified fine-medium sandstone. Occasional small scale scours with channel fill and trough cross-stratification. Occasional siltstone drapes. Sandstones interbed or grade into laminated siltstones and siltstone with thin lenticular or parallel beds of fine mudstone. Sandstone dykes, disrupted bedding.	Sandy floodplain sedimentation. Fine-medium sandstones deposited from advancing planar bedforms and filling minor scours. Siltstones deposited during waning flood stages. Liquefaction.

Fig. 5.8. Generalised succession and interpretation of the Kahurangi Formation.



Description	Interpretation
Carbonaceous siltstone or coal	
Massive or crudely stratified pebbly coarse sandstones to coarse sandy fine pebble conglomerates. Carbonised wood fragments. Silt-fine sandstone lined scours. Subangular fine pebbles of feldspar.	Accumulation of locally derived coarse detritus and peat in topographic lows with weathering profile and soil development. Peat, thin cycles suggest little differentiation of channel and overbank areas.
Silty fine sandstone with occasional plant stem, granule or pebble.	
Silicification, kaolinite, glaebules, in-situ rootlets.	

In the spectrum of fluvial environments, the Puponga Formation (Whanganui Inlet) occupies a position intermediate between the Brahmaputra and Indus Types (Fig. 5.3)

Kahurangi Formation: Description and interpretation of the Kahurangi Formation is outlined in Fig. 5.8. Lithologies are unlike those of the Pakawau Group in general. Relatively thin cycles containing coal, carbonaceous siltstone, minor silty fine sandstones and coarse sandstones to fine pebble conglomerate (Fig. 5.8), suggest little differentiation of channel and overbank sedimentation. Subangular fine pebbles of feldspar and poor sorting of fine pebble conglomerate and sandstone lithologies suggest little transportation and local derivation. The sedimentary and stratigraphic features suggest Kahurangi lithologies accumulated in low-lying swampy areas on a basement with gentle relief; nearby local highs supplied coarse granitic detritus.

The thin Kahurangi Formation is locally absent on the south side of Big River (see Kahurangi sections, back pocket, Stratigraphy). It is suggested that this location represents an original high.

Paleosols, Silcretes

The presence and association of cutans, sepic fabric, chertification, plant rootlets and kaolinization indicate paleosol and silcrete development at the top of the Farewell Formation (Kaihoka, Te Hapu), the Kahurangi Formation (Big River Section) and the uppermost part of the Puponga Formation (Whanganui Inlet). Soil and silcrete development requires a static weathering profile and indicates a prolonged period with little or no detritus accumulation.

Silcrete-forming conditions are indicated by the general features of extensive chertification and kaolinization, an association also described in silcrete profiles from Australia and South Africa (Smale 1973). In addition there is a close resemblance between pedogenetic features in the Pakawau Group and 'pseudo nodules', colloform structures and dilation veins (see Composition and Diagenesis) described in Australian silcretes (Williamson 1951).

In many silcretes with long-term stability, a profile is developed with duricrust in the upper part and less intense silicification accompanied by kaolinization in the lower part (Smale 1973, Grant and Aitchison 1970). The association of kaolinization and silicification is analagous to the lower part of well developed profiles. The top of the Farewell Formation (Kaihoka) is noticeably more indurated than other Pakawau Group lithologies, but no true duricrust is developed. The possibility of removal during transgressive reworking (see Interpretation of Nguroa Member) seems unlikely; no reworked clasts with remnant duricrust characteristics were detected.

Alteration of feldspar to kaolinite in the upper Farewell Formation (Kaihoka Section) is indicated by the absence of feldspar (quartzarenite, Fig. 4.1), high kaolinite content and pseudomorphing of feldspars in volcanic pebbles by kaolinite and chert (Pedogenesis, Fig. 4.18). It is also possible that kaolinite in cherty matrix may have been formed by alteration of matrix clays.

Silica may have been derived from kaolinization of feldspars (Smale 1973) or by a continuous wetting and drying action dissolving and depositing silica derived locally or elsewhere (Grant and Aitchison 1970). Warm, moist and temperate climatic conditions prevailing at the time of deposition of the Pakawau Group (Fleming 1962) would probably have been conducive to either process.

MARINE SEDIMENTATION ABEL HEAD FORMATION, TAKAKA LIMESTONE

General

Tidal, beach, minor prograding fluvial, and inner shelf environments are recognised in the Abel Head Formation. Shelf and inner shelf environments are recognised in the Takaka Limestone.

The range of structure and textures in tidal and beach environments is diverse. Tide-dominated environments develop along coasts that dip gently seaward, have marked tidal rhythms but little strong wave action, and occur in geomorphic settings ranging from protected lagoon to open and exposed (Reineck and Singh 1975, Ginsburg ed. (1975). Areal extent, degree of gullying and channelling, and size range of sediments are determined by geographic factors of tidal range, climate, tectonics of hinterland, and sediment supply by rivers. In any one tidal setting, associations of sedimentary structures and textures depend on response to different sedimentary and biological processes, in sub-environments distinguished as supratidal, intertidal and subtidal. A vertical profile will reflect retrogradational or progradational superimposition of subenvironments.

Beach environments also exhibit variation, e.g. high energy versus low energy, barred versus non-barred, and a range of subenvironments distinguished as shoreface, foreshore and backshore. Recognition and interpretation of tidal and beach environments, critical to determining the onset of transgression, minor progradational episodes and paleogeographic reconstruction, is achieved by analogy with a range of modern counterparts.

The terms 'inner shelf' and 'shelf' are used in the following context: 'inner shelf' ('transition zone' of Rieneck and Singh 1975) is used to denote the zone between beach and nearshore sandstones and shelf mudstones characterized by interbedded sandstone and mudstone, or sandy mudstone lithologies where bioturbation has destroyed original bedding features. 'Shelf' is used to denote the zone beyond the inner shelf characterized by mudstone (siltstone, micritic fine calcarenite) sedimentation.

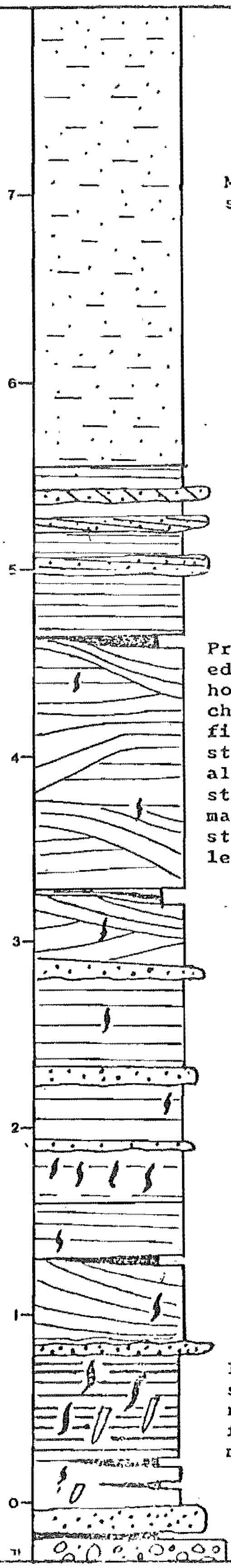
Tidal sedimentation (Te Hapu Member)

Thin lenses of marine bivalve and gastropod shell debris, and intensive and varied types of bioturbation, are indicative of a marine environment. Interbedding of massive, intensely bioturbate and weakly bioturbate laminated lithologies, interbedded lithologies ranging from pebble conglomerates to mudstones, and the presence of upward fining sequences with lithologies paralleling an erosional base (see Structures and Textures) characterize the Te Hapu Member. All the above features suggest a marine environment that is characterized by different bioturbation intensities, that is capable of transporting pebbles yet also capable of depositing mud from suspension, and that accumulates some sediments by a channel-fill process. A tidal environment is inferred.

Associations of sedimentary structure and textures of the Te Hapu Member (Te Hapu Section) are summarised in Fig. 5.9. Interpretation is based on general similarities and minor differences with recent tidal deposits of the North Sea (Reineck 1975), The Wash (Evans 1975), and others in Ginsberg ed. (1975). The association of mudstones and bioturbate fine sandy mudstones (Fig. 5.9) is interpreted as representing mixed flat sediments of the intertidal zone (Reineck 1975). Thin mudstones, minor alternating fine sandstones-mudstones, and laminated fine sandstones (Fig. 5.9) are interpreted as sand flat intertidal zone sediments (Reineck 1975, Evans 1975). Upward fining sequences overlying erosional surfaces are interpreted as deposits of small tidal gullies dissecting intertidal flats (Reineck and Singh 1975) or as small subtidal channel deposits. The origin of the massive muddy fine sandstone (Fig. 5.9) is uncertain. Fleming (1977) describes lower intertidal flats and subtidal flats with completely bioturbated, structureless sediments. Destruction of lamination to produce structureless sediments also occurs in vegetated supratidal and intertidal areas (Thompson 1975).

Flaser and lenticular bedding, along with small scale ripples, are common in the North Sea flat intertidal environments. In the Te Hapu Member, alternating fine sandstone-mudstone associations have even and parallel

Fig. 5.9. Succession and interpretation of the Te Hapu Member (Te Hapu).



Description	Interpretation
Massive muddy fine sandstone	Lower intertidal or subtidal flats. Vegetated intertidal or supratidal flats.
Predominantly mud laminated fine sandstone with horizontal or low angle channel-fill cross-stratification. Minor thin mudstones, thin parallel alternations of fine sandstone and mudstone, and massive or horizontally stratified coarse sandstone lenses Bioturbation intense to weak.	Tidal gullies and sand flat intertidal zone
Intensely bioturbate fine sandy mudstone with remnants of thin alternating fine sandstone and mudstone.	Mixed flat intertidal zone
Sandy fine pebble conglomerate (Nguroa Member).	Basal transgressive lag.

laminations (tidal bedding); small scale ripples are virtually absent and horizontal stratification predominates. Walker and Harms (1975) attribute the absence of channel structures in tidal environments to low tidal range, where flaser and lenticular bedding, characteristic of North Sea tidal deposits, is absent. Thompson (1975) notes that tidal flat currents moving over flats as broad uniform sheets fail to develop channels, and deposits typically exhibit uniform horizontal lamination. Small scale channels, and the predominance of horizontal and low angle cross-lamination in the Te Hapu Member, are interpreted as features of a tidal environment with a small tidal range.

Elsewhere (Anatori, Sharks Head and Kahurangi sections, back pocket) the Te Hapu Member displays a similar range of lithologies as those encountered in the Te Hapu section that are also interpreted as representing tidal environments.

Beach-nearshore and minor prograding fluvial sedimentation (Nguroa, Kaihoka and Lighthouse Members): The Nguroa Member is interpreted as a residual lag of Pakawau Group pebbles concentrated by beach processes.

Glauconite, *Ophiomorpha* burrows and the presence of brachiopod, bivalve and echinoderm debris, all indicate that that the Kaihoka Member was deposited in marine conditions. Well rounded and sorted granular coarse sandstones and fine pebble conglomerates indicate high energy depositional processes. Structure and texture associations have analogues in modern offshore, shoreface and foreshore environments; beach and nearshore environments are inferred.

Sections vary widely in lithological associaton; description and interpretation of three Kaihoka Member Sections are presented in Fig. 5.10.

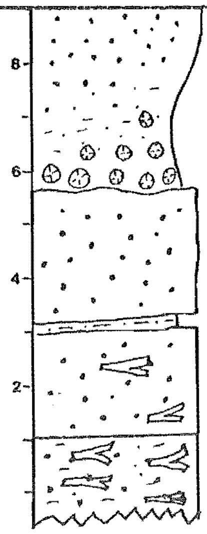
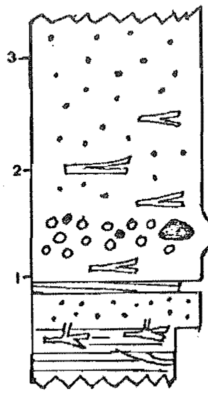
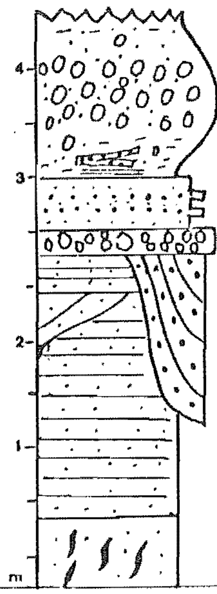
The Kahurangi Section (Fig. 5.10) exhibits the widest range of lithologies. Parallel and cross-laminated fine sandstones and muddy bioturbate fine sandstones (Fig. 5.10) are respectively described from the shoreface and beyond the shoreface zone in modern environments (e.g. Sapelo Island, Gulf of Gaeta reviewed Reineck and Singh 1975). Sorted, packed conglomerates and massive, well sorted coarse sandstones (Fig. 5.10, see Structures and Textures) are interpreted as shoreface lithologies. Interbedded horizontal or low angle cross-stratified well sorted fine sandstones (Fig. 5.10) are interpreted as upper shoreface or foreshore lithologies. Conglomerates up to 40 cm thick, and generally coarse and loosely packed sands, have been described from upper shoreface high energy non-barred beach environments (Clifton *et al.* 1971). Foreshore sands with horizontal and low angle cross-stratification are associated with shoreface conglomerates in high energy beach environments (Harms *et al.* 1973 after Clifton 1971).

The channel structure with channel-fill cross-stratified coarse sandstones, called here the Lighthouse Member (Fig. 5.10), is interpreted to result from a scouring and filling event following discharge of coarse grained fluvial sediments into a beach-nearshore environment. The association of structures and textures of the Lighthouse Member south of Kahurangi Point (see Kahurangi section, back pocket, Structures and Textures) is characteristic of fluvial sedimentation. The succession from offshore, lower and upper shoreface, and possible foreshore deposits is interpreted as a prograding beach sequence deposited in response to a prograding fluvial episode.

Conglomerate to siltstone lithologies overlying the shoreface conglomerate association (Fig. 5.10, Kahurangi Section) represent a brief episode wherein beach-derived, rounded and sorted pebbles and coarse sandstones prograded on to shelf silts. Coarse sandstones and fine pebbles transported shelfward were deposited as irregular lenses or infilled open burrow structures, and subsequent biogenic reworking produced a massive silty to granule-pebble conglomerate.

The Kaihoka, Te Hapu and Abel Head Sections are characterized by thick, massive, well rounded and sorted, granular coarse sandstones. Abundant *Ophiomorpha*, in the absence of other biogenic and sedimentary structures, suggests a littoral environment (Weimer and Hoyt 1964, see Biogenic Structures). Accumulation in a relatively low energy environment is suggested by an often high matrix content (Fig. 3.10, Structures and Textures), a thin interbedded silt lense, and a glauconitic bed with lobate coarse sand size glauconite (Fig. 5.10, see description and interpretation of glauconite). Progradation of beach derived, sorted and rounded sands into a nearshore-shelf environment, is suggested by the occurrence of well rounded and sorted coarse sandy mudstones that characterize the transitional contact with the Turimawiwi and Rakopi Members (Kahurangi and Abel Head Sections respectively, see back

Fig. 5.10. Succession and interpretation of the Kaihoka Member (Abel Head, Te Hapu-Kaihoka and Kahurangi).

Section	Column	Description	Interpretation
Abel Head		Glauconitic siltstone (Rakopi Member) overlying erosional surface, grading into massive coarse sandstone.	Nearshore sands prograding into inner shelf.
		Massive granular very coarse to coarse sandstone with varying intensity of <u>Ophiomorpha</u> burrowing and mud content.	Beach-nearshore environments indistinguishable, several episodes of progradation.
Te Hapu Kaihoka		Massive granular very coarse to coarse sandstone. Weathering differentiates distinct beds - different intensities of bioturbation ? .	Beach-nearshore environments indistinguishable, several episodes of progradation.
		Pebble conglomerate and rounded clasts of concretionary fine sandstone. Thin horizontally stratified fine sandstone.	Reworked early formed concretions and foreshore conglomerates.
		Horizontal and trough fill cross stratified fine sandstone.	Shoreface sediments.
Kahurangi		Siltstone with occasional remnant lamination grading into and from coarse sandy fine pebble conglomerate. Toward base fine pebbles form thin lenses and infill burrows.	Coarse sand to fine pebbles reworked from beach-nearshore environments to inner shelf.
		Interbedded massive and burrowed, horizontally stratified sandstones, coarse sandstones and massive pebble conglomerates.	Upper shoreface and foreshore sediments.
		Large scale channel with channel-fill cross-stratified granular very coarse sandstone.	Fluvial channel sediments.
		Horizontal and cross-stratified fine sandstone.	Lower shoreface sediments.
		Massive bioturbate fine sandstone.	Shelf sediments.

pocket). Intervals of erosion and non-deposition are suggested by sharp contacts between coarse sandstones with varying mud content, a minor paraconformity at the Abel Head Section (Fig. 5.10), and the common absence of the upper vertical tube part of *Ophiomorpha* burrows. Locally at Kaihoka and Te Hapu, conglomerate is sandy and grades to and from coarse sandstones, and in this respect is unlike the packed conglomerates with sharp contacts at Kahurangi. Reworking of conglomerate, probably from a shoreface environment, is suggested by their association with spheroidal sideritic concretions which are interpreted as having been reworked from underlying fine sandstones (see Structures and Textures and Interpretation-siderite authigenesis below).

Siderite authigenesis (in tidal, beach-nearshore and inner shelf sediments): The optimal chemical environment for siderite is one of low Eh, high a.Fe^{2+}, high a.CO_2, low a.$SO_4^{=}$. Siderite is not stable at Eh values of well aerated normal sea-water but is stable at lower Eh values within sediment pore water. Unless a.$SO_4^{=}$ is low, bacteria reduce $SO_4^{=}$ to $S^{=}$ and pyrite is preferentially formed (Curtis and Spears 1968, Taylor and Spears 1965, Huber 1958, Sellwood 1971). Of application to the occurrence of a high siderite concentration in the Rakopi Member (see description of siderite) is the model proposed by Sellwood (1971). Under reduced sedimentation rates, Fe^{2+} that has been mobilised under anaerobic conditions, can either oxidize when it moves into an oxidizing environment (sediment-water interface), or form pyrite by reaction with

$SO_4^{=}$. Surfaces which remain close to the sediment-water interface for long periods effectively concentrate Fe^{2+}. Upon renewed sedimentation, this zone of concentrated Fe^{2+} returns to reducing conditions, and recently deposited sediment provides a barrier to $SO_4^{=}$ migration from overlying sea-water. Fe^{2+} cannot form pyrite and is available to form siderite.

Similar conditions are envisaged for siderite formation in the massive Kaihoka and Rakopi Members. Reduced sedimentation rates, a necessary requisite for this model, are also generally indicated by high glauconite concentrations, the massive bioturbate character and minor breaks in sedimentation (see Rakopi, Kaihoka, Turimawiwi Members, Abel Head, Kaihoka and Te Hapu Sections back pocket). The occurrence of siderite in bedded Te Hapu lithologies is less compatible with a low sedimentation rate; instead of Fe^{2+} concentrating under conditions of reduced sedimentation rate, a locally concentrated source of Fe^{2+} is provided by exsolution from altered biotite (see description of siderite).

An early diagenetic origin of siderite is suggested for sideritic concretions in well sorted fine sandstones of the Kaihoka Member (see Kaihoka Member, Te Hapu and Sharks Head Sections and description of spherical, spherical-attenuated structures Kaihoka Member). It appears that early precipitation of concretionary siderite formed resistant structures which were reworked and physically transported, or formed resistant masses from around which surrounding fine sand was removed (Fig. 3.9).

The concretions are interpreted as lag deposits.

Inner shelf - shelf sedimentation

The Turimawiwi, Rakopi, Paturau and Anatori Members represent inner shelf and shelf environments, with successive detrital, glauconitic and carbonate sedimentation.

Turimawiwi Member: The generally massive and bioturbate Turimawiwi stiltstone is interpreted as a shelf deposit.

Thin coarse sandy intercalations at the base of the Turimawiwi Member (see Structures and Textures, Kahurangi, Te Hapu Sections) are interpreted as beach and nearshore derived coarse sands (rounding and sorting of coarse sands resembles Kaihoka Member coarse sandstones) transported to an inner shelf environment, possibly by storm reworking processes (modern analogue 'transition zone' Büsum region North Sea, Reineck and Singh 1975). Biogenic reworking has disseminated coarse sand.

Rakopi Member: The massive, bioturbate, glaucarenite and glauconitic sandy biomicrites of the Rakopi Member are interpreted as shelf and inner shelf deposits.

Glauconite formation is favoured under conditions of low sedimentation rate (MacRae 1972). Lobate forms are comparatively fragile and their common occurrence is indicative of accumulation close to the site of formation (Triplehorn 1966). Phases of multiple accretion are favoured by bottom environments with gentle current activity (Bailey and Atherton 1964). Fine to medium sand size spheroidal-ovoidal glauconites may have been formed with initial spheroid-ovoid shape, or be the products of abrasion of other types of pellets (Triplehorn 1966, McConchie and Lewis 1977). Fragmentation of lobate grains, without rounding to produce spheroidal-ovoidal types, is indicative of either an intermediate energy event or less continuous energy input. Glauconite altered to limonite is indicative of a previous history of oxidation; possibly by subaerial oxidation and subsequent reworking (e.g. Chillingar 1956).

Subenvironments of the shelf to inner shelf are suggested by variation in glauconite character.

At Abel Head, and in the upper Rakopi Member at the Te Hapu Section, shelf sedimentation with gentle current activity is suggested by a high proportion (60-70%) of predominantly lobate glauconite with minor fragmentation and multiple accretion features and minor micrite sedimentation.

The basal Rakopi Member at Te Hapu, exhibits an association of features suggestive of more proximal inner shelf sedimentation than the upper Rakopi Member at the Te Hapu Section, and the entire Rakopi Member at the Abel Head and Kahurangi Sections. Reworking of glauconite is suggested by the predominance of fine sand size ovoidal-spheroidal glauconites (Table 4.2). Associated, well rounded coarse sands are interpreted as derived from beach-nearshore lithologies (see interpretation of Turimawiwi Member). Fragmentary, limonitized glauconites have probably been reworked from a subaerially exposed environment.

At Kahurangi, shelf sedimentation with more active current activity (cf. Rakopi Member, Abel Head, upper Rakopi Member, Te Hapu) is suggested by a relatively low proportion (40%) of predominantly fine-medium sand size spheroidal-ovoidal glauconites associated with fine sand size carbonate allochems.

Paturau and Anatori Members: Textural and faunal changes reflect a change from low energy pelagic sedimentation (Paturau Member) to current swept shelf environments supporting benthic fauna (Anatori Member). The massive and bioturbate micritic fine calcarenite (Paturau Member) is interpreted as representing a low energy environment; varying amounts of micrite reflects variation in micrite supply or current activity, and the high proportion of planktonic foraminifera reflects significant pelagic sedimentation.

Winnowing of micrite, transport and moderate sorting of medium-coarse allochemical and detrital components and locally, lag concentration of granule to very coarse detrital sands indicates the Anatori Member (cf. Paturau Member) was deposited by more active current activity. Detailed environmental analysis and interpretation was beyond the aim of this thesis. However, the general association of echinoderms, bryozoans, benthonic foraminifera and minor rhodolites is suggestive of a current swept shelf environment (Milliman 1974, Adey and MacIntyre 1973, Wass *et al.* 1970).

COMPOSITION

The presence of granite pebbles in the Farewell Formation, the generally feldspathic nature of Pakawau Group sandstones, and the heavy mineral assemblage (see Composition) indicate a substantial contribution from granitic terrain. Volcanic, schistose and sedimentary conglomerate clasts also occur. Paleocurrent data (Fig. 3.13) suggests derivation from the south-east and east in the Golden Bay to Heaphy River vicinity, which contains granites, volcanics, schistose and sedimentary types. The generally high percentage of biotite in the North Cape, Puponga and lower Farewell Formations is suggestive of rapid derivation and deposition. The association of fresh and extremely altered feldspars and variation of alteration within one type of feldspar suggests that feldspar freshly derived from parent rock, and altered feldspars derived from weathering profiles of previously deposited sediments, were incorporated in later deposits.

In the upper Farewell Formation, the absence of feldspar in some lithologies and the development of soil and silcrete features (see Composition and Diagenesis) reflect an increased tendency for stabilization and storing of sediments within a weathering profile. Under conditions of reduced supply of freshly derived sediment, reworking of sediments previously stored within a weathering profile resulted in less feldspathic or entirely quartzose sandstones, removal of biotite, an increase in the proportion of quartzarenite and quartz vein pebbles, and a corresponding decrease in the proportion of granitic and volcanic clasts.

Concentration of feldspar relative to quartz in fine sandstone lithologies of the Kaihoka and Te Hapu Member lithologies, and the Pakawau Group (see Feldspars, Composition), is interpreted to be a result of features favouring more rapid size reduction in feldspar, namely cleavage and relative softness (Folk 1968). Rounded, fresh to slightly altered coarse sand to granule size feldspars in the Kaihoka Member (see Composition) are interpreted to be reworked from Pakawau Group lithologies (see interpretation of Lighthouse Member). Altered feldspars have probably been comminuted in a high energy beach environment (see interpretation of Kaihoka Member) and concentrated relative to quartz in the finer sediment fractions.

In the Abel Head Formation and Takaka Limestone, the general trend from terrigenous to glauconitic and carbonate sedimentation (Fig. 4.2A) reflects declining availability of terrigenous sands and clays, in response to increasing distance from the shoreline and/or reduced topography of the hinterland. Glauconite formation and accumulation of highly glauconitic lithologies was favoured whilst detrital clay input and availability of terrigenous and carbonate detritus was low. The rapid change from glauconitic to calcarenite sedimentation (Abel Head, Te Hapu sections) is interpreted as representing a sudden increase in the availability of carbonate and initially minor terrigenous detritus, as a result of increased current activity and sedimentation rates. Locally high concentrations of terrigenous grains in the Anatori Member are interpreted to be derived from residual landmasses,

whence they were transported by active shelf currents (see interpretation of Anatori Member).

CHAPTER VI

SYNTHESIS

Pakawau Group sedimentation began in the Whanganui Inlet vicinity during the early Upper Cretaceous, with deposition of 400 m of Otimataura Conglomerate on a basement surface with some relief (Bishop 1968, 1971). The depositional basin of the Pakawau Group was initiated by movements on the Wakamarama Fault (Bishop 1971); rapid uplift to the south-east supplied sediments to the rapidly subsiding north-west. Paleocurrent data (Fig. 3.13) suggests the eastern source - western basin of accumulation relationship continued until late Cretaceous - early Paleocene times.

By the end of late Cretaceous time, the Abel Head - Whanganui Inlet and Cook I vicinities had respectively accumulated 1000 m and 2500 m of fluvial sediment. A proximal-distal relationship, between the Whanganui Inlet and Cook I vicinities, is suggested by south-west to south-east paleocurrent directions (Fig. 3.13), a general fining from the Whanganui Inlet-Abel Head vicinity to the Cook I vicinity, and the occurrence in the Cook I Section of a general coarse-fine-coarse sequence similar to that exhibited in the Abel Head-Whanganui Inlet vicinity. Large amounts of finer sediment probably bypassed the Whanganui Inlet-Abel Head vicinity. Thickening westwards is interpreted to be a result of downthrow on the west of a series of northeast-southwest trending faults (Fig. 6.1). Basement collapse and graben type structures are a characteristic feature of regions west of the Alpine Fault in Cretaceous times (Katz 1976).

In the Kahurangi region, the Pakawau Group is represented by comparatively thin (0-15 m) Haumurian sediments that were locally derived and accumulated in a swamp environment in topographic lows on leached granite basement (see Interpretation of Kahurangi Formation, Paleosols and Silcretes). Alternative explanations for the difference in thickness of the Pakawau Group at Kahurangi and Abel Head-Whanganui Inlet are: significant thicknesses accumulated in both vicinities, but later the Kahurangi area was uplifted and sediment removed, or basement in the Kahurangi vicinity was always and remained high, possibly bypassing sediment at times, whilst the Whanganui Inlet-Abel Head vicinity subsided.

During the Haumurian represented by the North Cape Formation, braided stream sedimentation ranged from conglomeratic in the north, to sandy and with well developed muddy overbank sedimentation in the southern Whanganui Inlet vicinity (Fig. 6.1). Paleocurrent data, indicating transport from the south and the south-west, suggests the northeast-southwest conglomerate sandstone facies change represents local variation in uplift and supply in adjacent areas, rather than a proximal-distal facies change.

The onset of floodplain conditions (Whanganui Inlet), with local accumulation of peat (Puponga) and general upward fining in the Puponga Formation, indicates diminishing

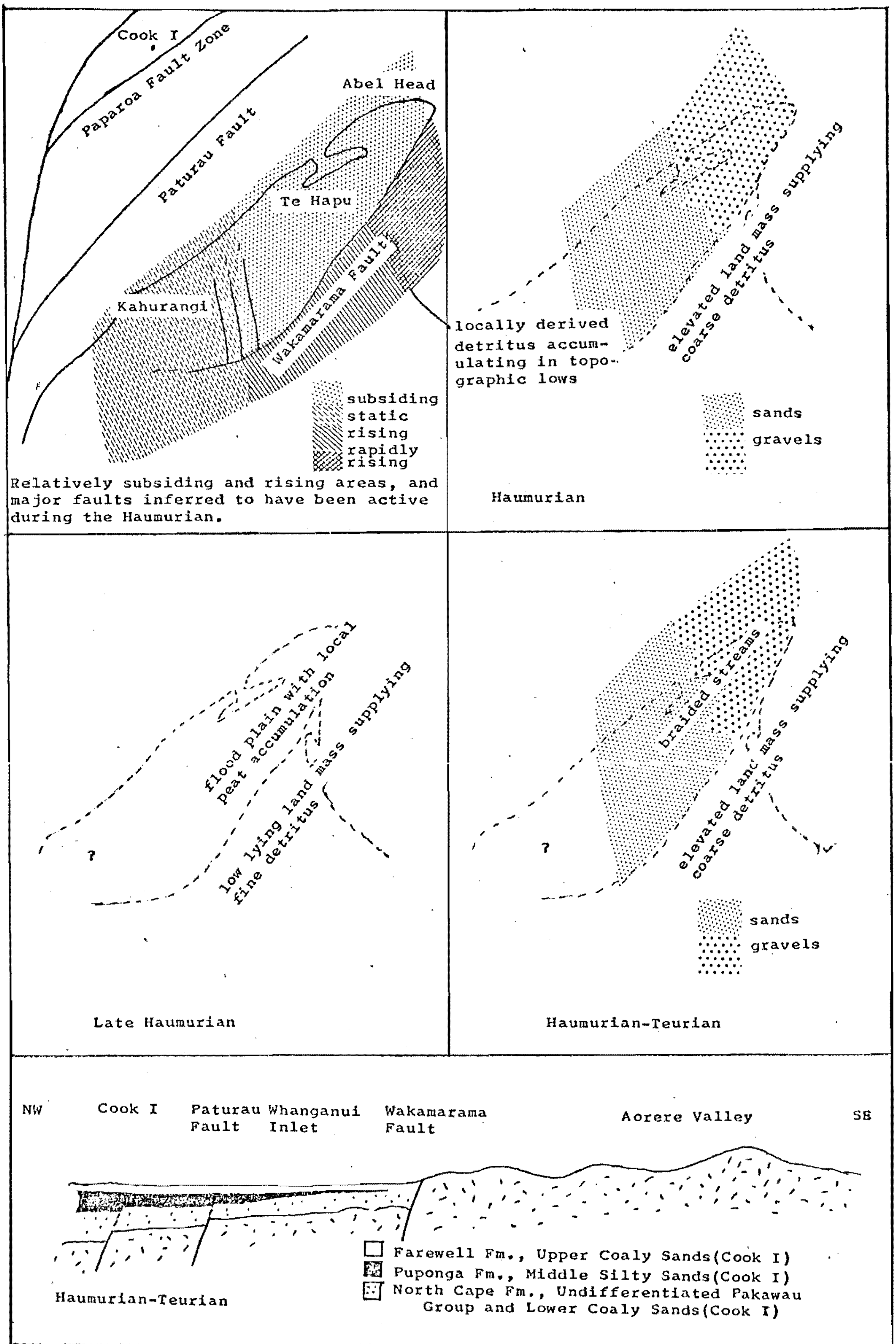


Fig. 6.1. Paleogeographic reconstruction of the Cape Farewell-Kahurangi vicinity, Hamurian-Teurian times.

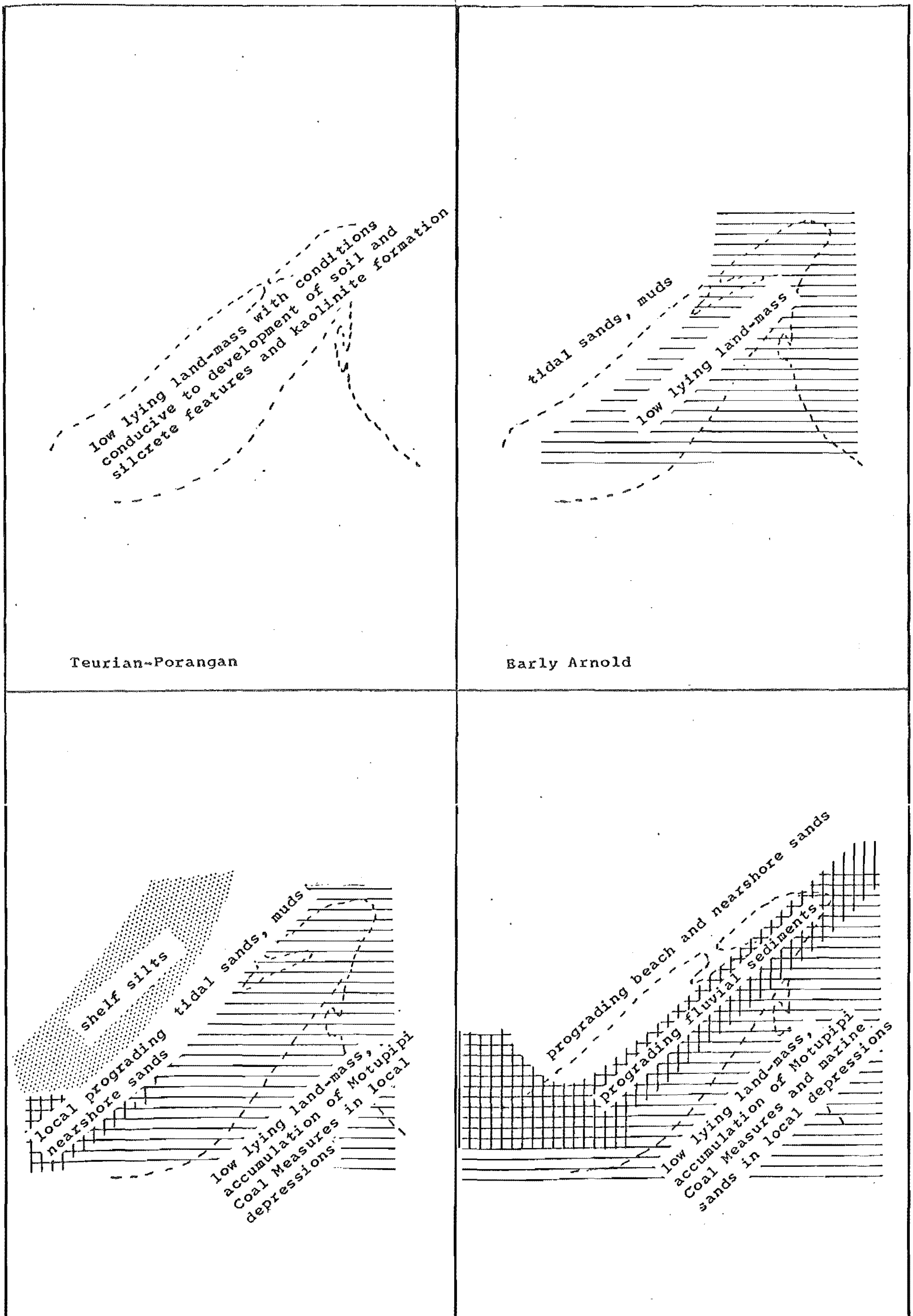


Fig. 6.2. Paleogeographic reconstruction of the Cape Farewell-Kahurangi vicinity, Teurian-Whaingaroan times.

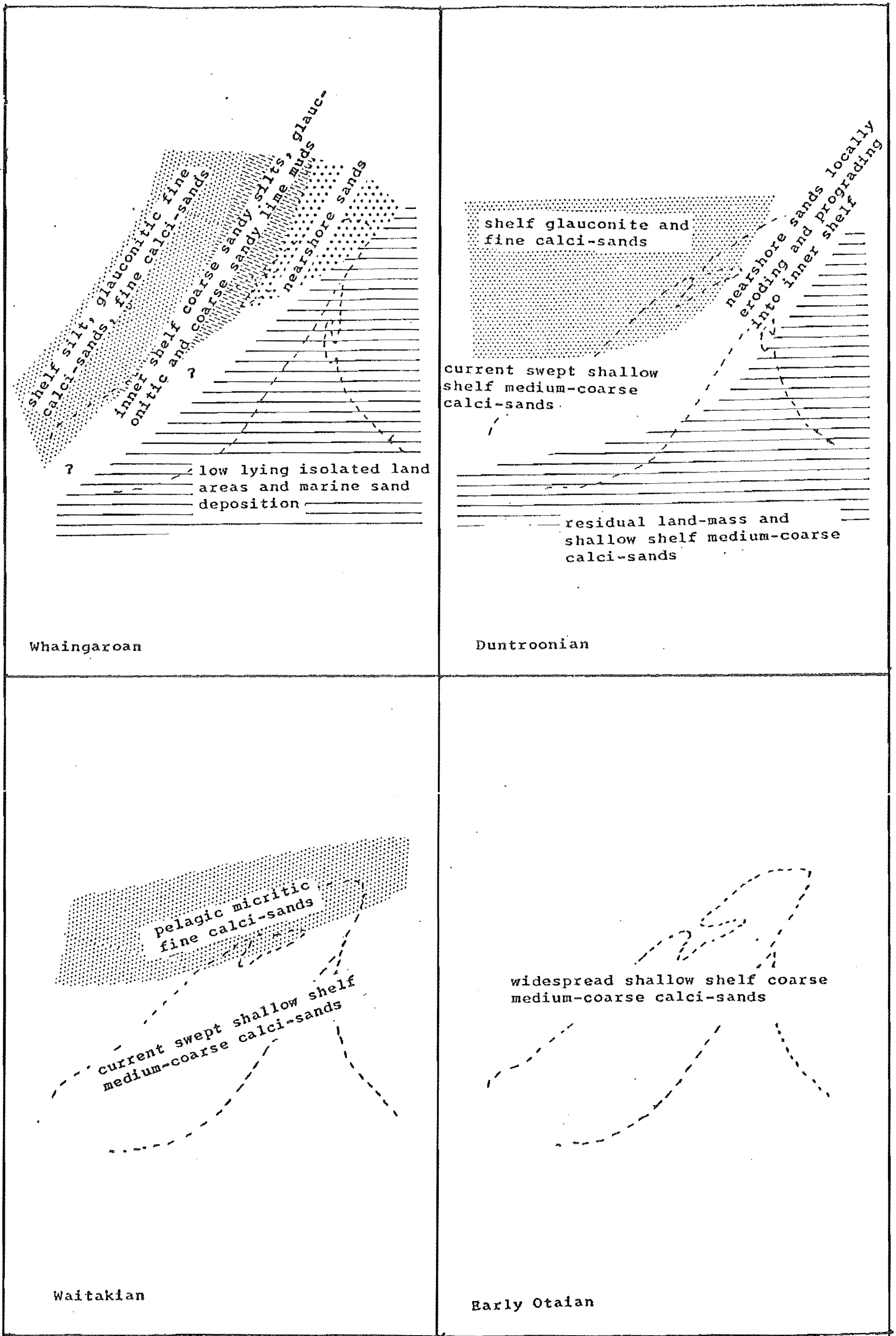


Fig. 6.3. Paleogeographic reconstruction of the Cape Farewell-Kahurangi vicinity, Whaingaroan-Otaian times.

relief and tectonic activity in the hinterland (see Fig. 6.1). Soil and silcrete features, at the top of the Puponga Formation (see Paleosols, Silcretes), indicate development of a stable weathering profile. The Cook I region continued to subside more rapidly, accumulating 1000 m of predominantly silty quartz sand, alternating with siltstones and minor conglomerates (Appendix I), whilst in the Puponga Region only 50 m of fine sands, silt and peat accumulated.

A sudden increase in tectonic activity is indicated by the sudden upward change to conglomeratic braided stream sedimentation (Farewell Formation), which continued from late Haumurian until Teurian times (see Fig. 6.1). The northeast/southwest conglomerate - sandstone facies change (cf. North Cape Formation) is interpreted as representing local variation in uplift. Differential subsidence continued with the Whanganui Inlet, Abel Head and Cook I vicinities each respectively accumulating 400 m, 800 m and 800 m of fluvial sediments. Pedogenic and silcrete features, and increasing mineralogic maturity at the top of the Farewell Formation, indicate declining tectonic tempo and quiescence, as both source and the basin of accumulation approached peneplain conditions during Teurian times (Fig. 6.2).

There is no record of late Cretaceous-Arnold, Teurian-Arnold, Teurian(?)-Whaingaroan(?) sedimentation at the respective localities of Kahurangi, Te Hapu, Abel Head. Marine sedimentation began in the Arnold in the Kahurangi vicinity, and probably did not commence in the Abel Head vicinity until Whaingaroan times (Fig. 6.2).

During the Arnold, at both Kahurangi and Te Hapu, minor reworking of upper Pakawau lithologies and concentration of gravels as beach deposits (Nguroa Member) preceded intertidal deposition (Te Hapu Member). Locally in the Kahurangi vicinity, as subsidence continued and shoreline migration progressed eastward, shelf mudstones, very fine sandstone (Turimawiwi Member) and locally prograding Kaihoka sands were deposited (Fig. 6.2).

At Kahurangi, during late Arnold-early Whaingaroan times, fluvial sediments (Lighthouse Member) prograded and cut through beach-nearshore lithologies (Fig. 6.2). Kaihoka Member coarse sandstones in the Kahurangi vicinity are interpreted as beach and nearshore environments prograding in response to supply by prograding fluvial sediments. South of Kahurangi Point, the occurrence of fluvial sediments resting directly on shelf lithologies (Turimawiwi Member, see Stratigraphy) suggests local uplift. Limited paleocurrent data (Fig. 3.13) suggests local transport from the north-west and west. Kaihoka Member coarse sandstones at Te Hapu and Abel Head are similarly interpreted as prograding beach and nearshore environments; the direction of progradation is uncertain. The progradational event produced a continuous sheet sandstone extending from Kahurangi to Abel Head (Fig. 6.2). Progradation of beach-nearshore lithologies was diachronous; in the Kahurangi vicinity progradation began and ended in late Arnold-early Whaingaroan times, at Abel Head progradation probably began during late Whaingaroan-early

Duntroonian times and continued during the Duntroonian. The episode of progradation recorded in the Kahurangi-Cape Farewell vicinity is probably part of a more widespread event in which Eocene Motupipi Coal Measure sandstones, and sandstones probably of marine origin, were derived and deposited in local depressions to the west of the Wakamarama Fault in the Takaka region.

Divergent sedimentary histories, following the late Arnold-Whaingaroan progradational event in the Kahurangi and Te Hapu-Abel Head vicinities, indicate varying basinal subsidence. Initially (Whaingaroan-Duntroonian) the Kahurangi vicinity subsided continuously, whilst the Abel Head-Te Hapu vicinity remained relatively static. Later (Waitakian) the Kahurangi vicinity became static, whilst the Abel Head vicinity subsided.

In the Kahurangi vicinity, 100 m of shelf sediments, exhibiting a gradational change from siltstones (Turimawiwi Member, 30 m), to glauconitic fine calcarenites (Rakopi Member) and finally fine calcarenites (Paturau Member), were deposited during Whaingaroan-Duntroonian times (see Figs 2.4, 6.3).

In the Te Hapu vicinity, thin inner shelf sandy siltstones (Turimawiwi Member, 1.5 m - cf. Kahurangi vicinity) and inner shelf glauconitic and coarse sandy biomicrites were deposited during Whaingaroan-Duntroonian times (see Figs 2.4, 6.3). In the Abel Head vicinity, glauconite (overlying minor unconformities) and prograding coarse sands, derived by local reworking of beach-nearshore sandstones, accumulated in an inner shelf environment. In both localities, low rates of interrupted sedimentation are characterized by minor unconformities and authigenic siderite formation.

The change to medium-coarse calcarenite sedimentation (Anatori Member), suggesting current swept inner or shallow shelf conditions, began in the Kahurangi vicinity during the Duntroonian. Locally, high concentrations of terrigenous detritus at Kahurangi (Composition - Description, Interpretation) were probably derived to the south and south-east. In the Aorere Valley, the Takaka Limestone rests directly on basement (Appendix I), indicating that basement was locally exposed at least until Whangaroan-Duntroonian times.

At Abel Head, the rapid change from sedimentation characterized by minor paraconformities, beach-nearshore sands and glauconite, to continuous shelf fine calcarenite (cf. Kahurangi) marks the beginning of subsidence during the Waitakian, following relatively static conditions since early Paleocene times. At Abel Head, the Waitakian is represented by 60 metres of fine calcarenite limestone. Medium-coarse calcarenite sedimentation (Anatori Member) did not begin until late Waitakian times (cf. Kahurangi, Abel Head, Fig. 6.3). By late Waitakian times, medium-coarse calcarenite sedimentation, reflecting shallow current swept shelf conditions, prevailed throughout the Kahurangi-Cape Farewell region.

During the early Miocene, calcareous siltstones (commonly glauconitic) were deposited, and sedimentation was accompanied by gentle folding and tilting during the middle and late Tertiary (Bishop 1971).

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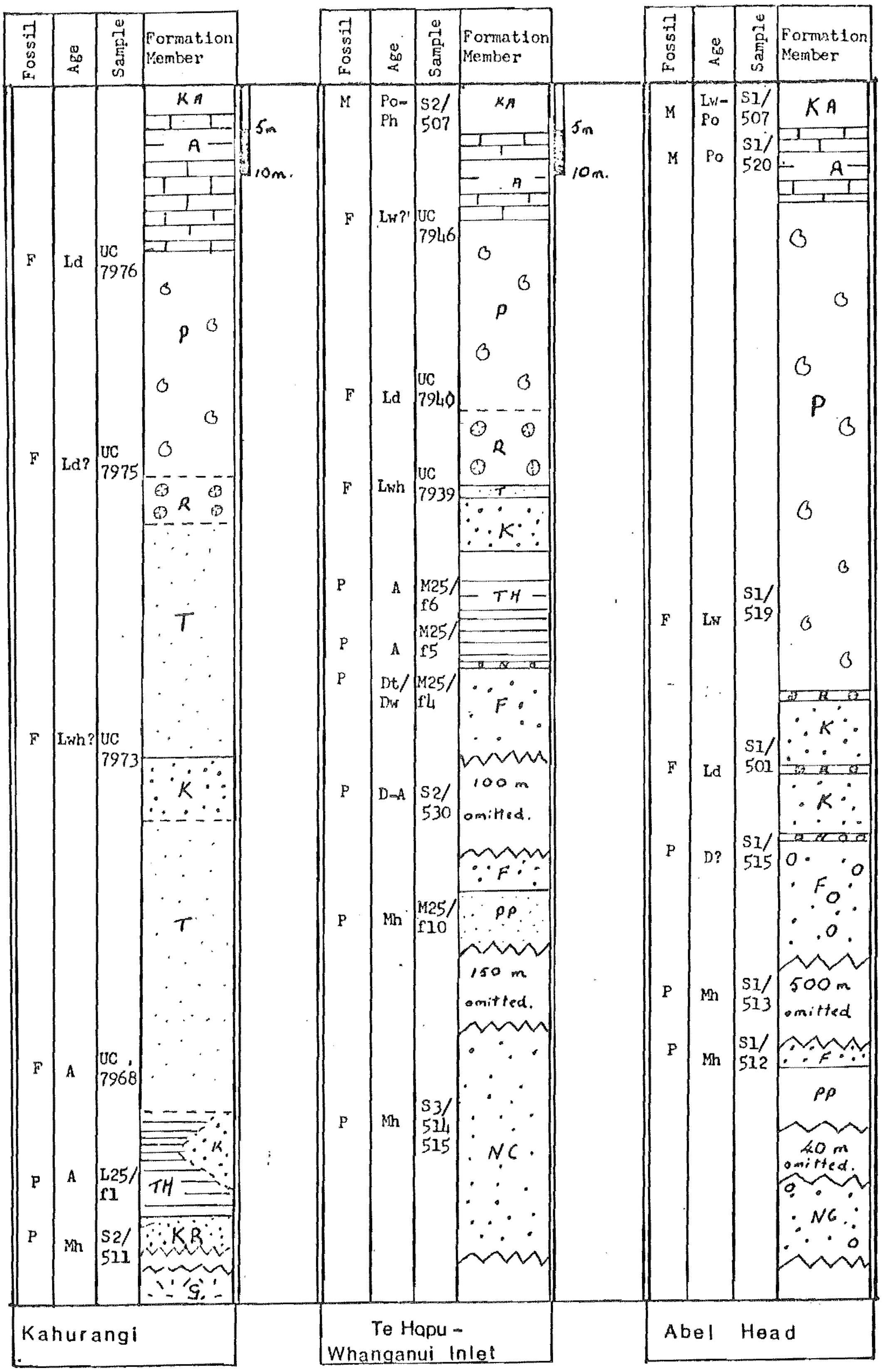
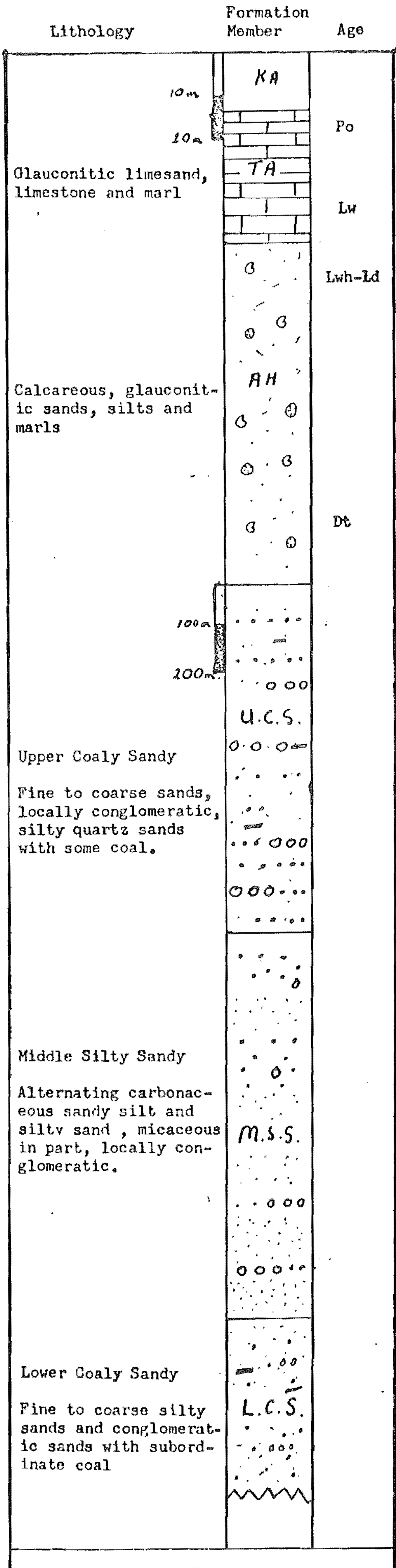
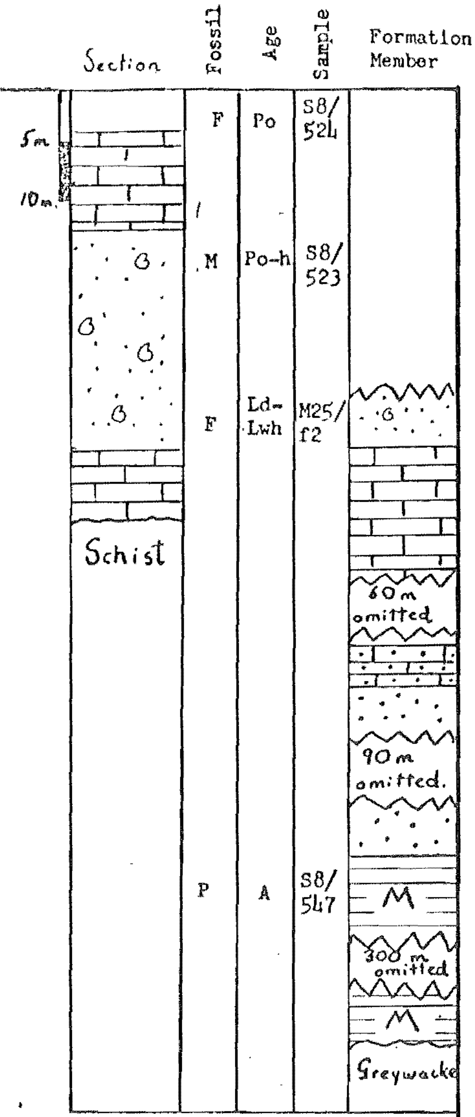
APPENDIX I



Location and details of age determinations Abel Head, Te Hapu-Paturau River, Kahurangi, Aorere Valley and Cook I Sections, and description of the Cook I Section(based on this study, Wellman, Beck et al. 1973, N.Z. Aquitane Petroleum Ltd., 1970). Key located following page.



COOK 1



Aorere Valley

Rangihaieta Head

Key

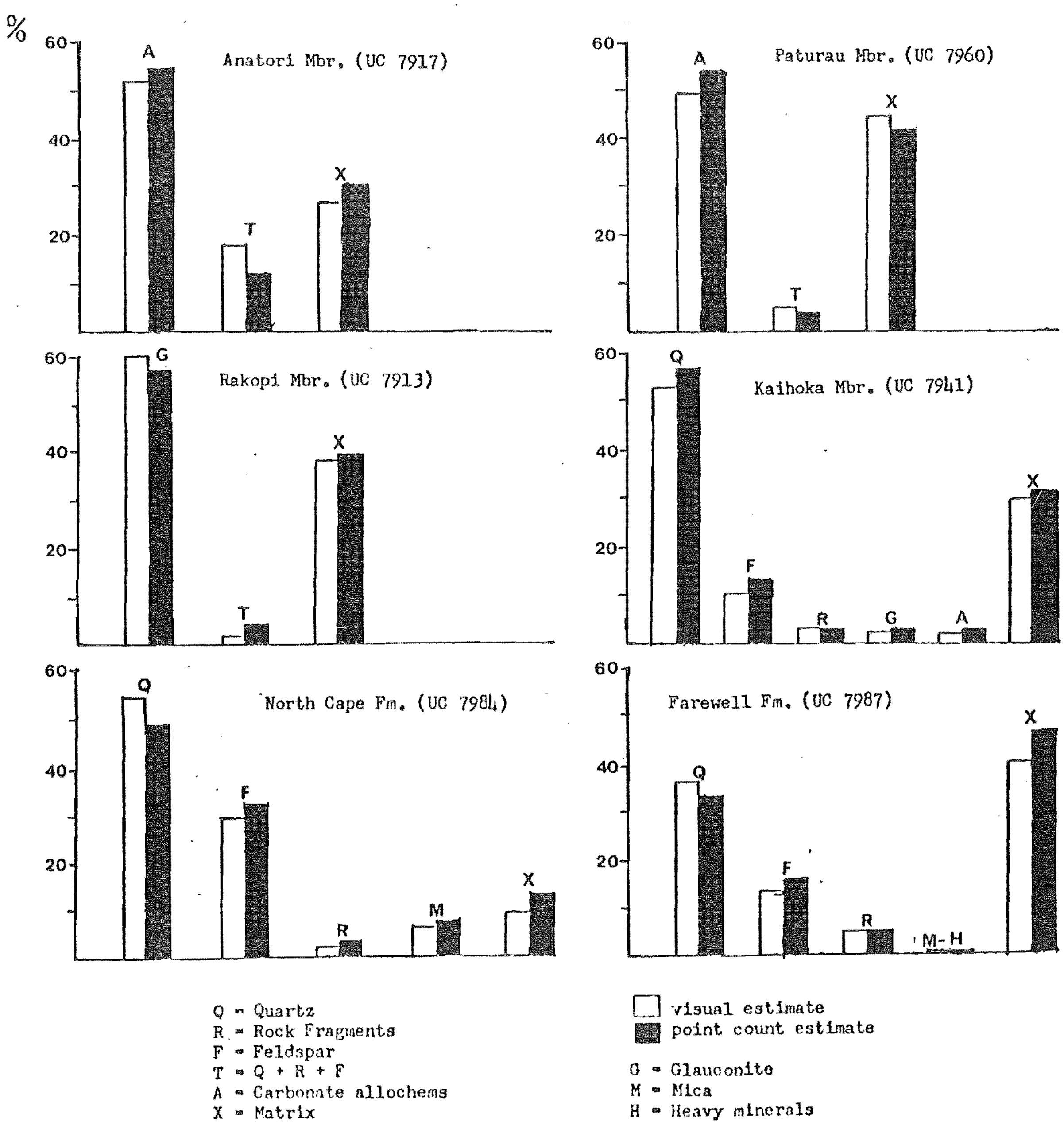
Series, Stages		Stratigraphy	
Po	Otaian	TA	Takaka Lst.
Lw	Waitakian	A	Anatori Mbr.
Ld	Duntroonian	P	Paturau Mbr.
Lwh	Whaingaroan	AH	Abel Head Fm.
A	Arnold	R	Rakopi Mbr.
D	Dannevirke	T	Turimawiwi Mbr.
Dt	Teurian	K	Kaihoka Mbr.
Dw	Waipawan	TH	Te Hapu Mbr.
M	Mata	N	Nguroa Mbr.
Mh	Haumurian	F	Farewell Fm.
		PP	Puponga Fm.
		NC	North Cape Fm.

F Foraminifera
M Macrofossils
P Microflora

Appendix I contd.

APPENDIX II

Components determined by visual comparison methods (charts of Folk *et al.* 1973) and point count estimation involving 300-400 points per sample exhibit discrepancy of the order of several per cent (0-6%, see below). Feldspar, carbonate allochems and matrix/cement were consistently underestimated by several per cent, other components were either over- or underestimated.



APPENDIX III

A volumetric estimation of lithologic percentages of pebble-cobble conglomerates was determined as follows. Several one metre grids were selected. The longest axes of gravel components were measured, and if greater than 64 cm (-6ϕ) components were classified according to composition, and allocated to one of three basic shapes. Fifty-five cobbles were measured. Three basic shapes - spherical, intermediate and blade - are defined by the following axial and volumetric ratios. The volumetric and axial dimensions of a sphere are taken to be unity.

Shape	L × I × S	Volumetric Ratio
Spherical	1 × 1 × 1	1
Blade	1 × 1/2× 1/4	1/8
Intermediate	1 × 3/4× 1/2	3/8

Relative volumes were estimated by multiplying the longest axis (in mm) by 1, 1/8 or 3/8 according to cobble shape for each cobble. Lithologic percentages were calculated by summing relative volumes for each lithologic type (after Cutten 1976).

APPENDIX IV

Sample Location

U.C. Sample Nos.	Location	
7901 - 7917	Abel Head	M24 876763
7918 - 7921	Cape Farewell	M24 859782
7922 - 7923	Anatori	M25 515545
7924, 7927	Kaihoka	M24 742728
7928 - 7935	Kaihoka	M24 742728
7936 - 7953	Te Hapu	M25 696683
7954 - 7963	Te Hapu	M25 685675
7964 - 7965	Sharks Head	M25 666664
7966 - 7970	S. of Kahurangi Pt. Lighthouse	L25 437475
7971 - 7975	S. side of Big R.	L25 453483 to L25 476483
7976 - 7979	N. side of Big R.	L25 462470
7980	S. of Kahurangi Pt. Lighthouse	L25 437475
7981	South Head Cone	M25 707690
7982 - 7985	Whanganui Inlet	M25 687652
7986	N. side of Big R.	L25 473483
7987	Kaihoka	M24 742728
7988 - 7989	Te Hapu	M25 696683
7990	South Head Cone	M25 707690
7991 - 7992	Whanganui Inlet	M25 703678
7993 - 7995	Whanganui Inlet	M25 685652
7925 - 7976	Whanganui Inlet	M25 708685

KEY

in Size

L SAND MUD

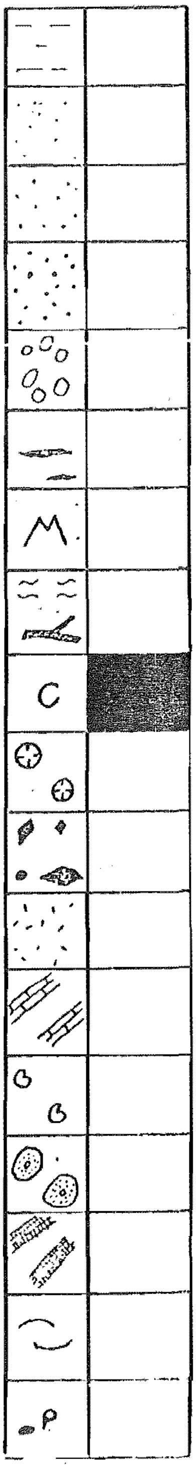
granule, very coarse, coarse, medium, fine, very fine, sandy mud, silt, clay

ABEL HEAD FORMATION AND TAKAKA LIMESTONE MEMBERS

- TA Anatori
- P Patarau
- R Rakopi
- T Turimawiwi
- K Kaihoka
- L Lighthouse
- TH Te Hapu
- NG Nguroa

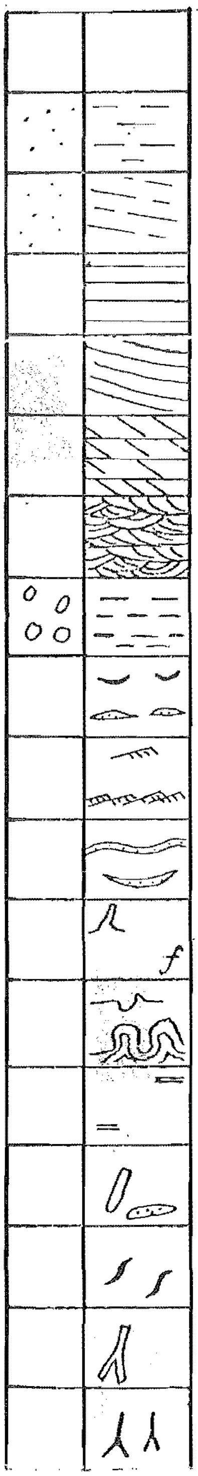
osition

COMPONENTS



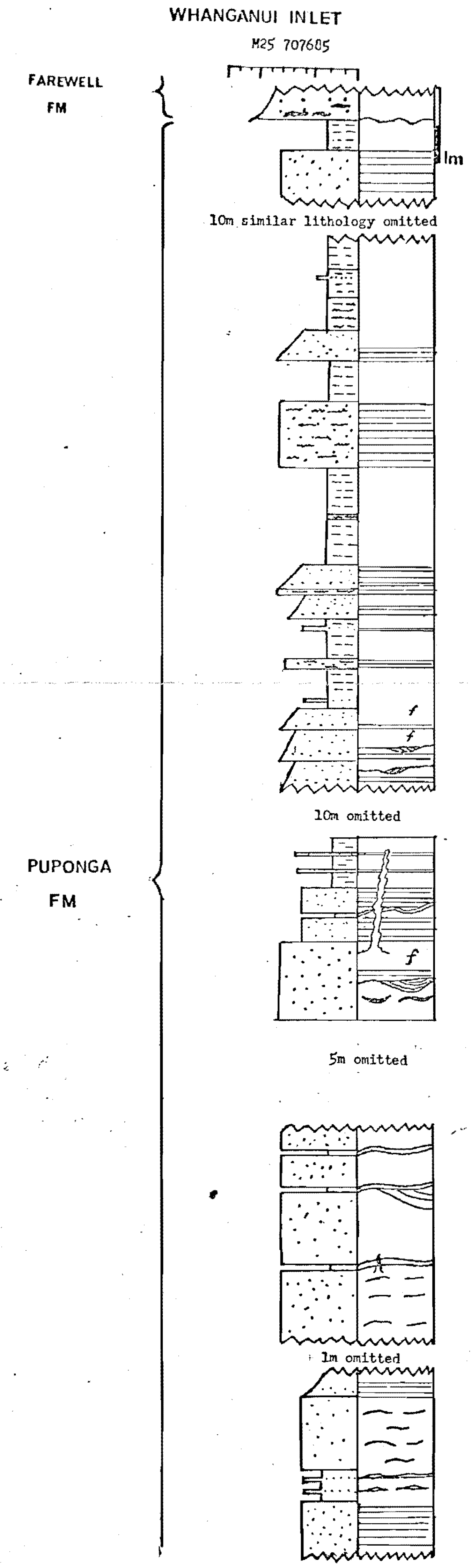
- clay
- silt
- very fine, fine sand
- medium-very coarse sand
- extraformational gravel clasts
- intraformational gravel clasts
- mica
- fine carbonaceous debris
- coaly stems
- coal
- glauconite
- siderite
- siderite concretions
- micrite-microspar
- bryozoa
- foraminifera
- echinoderm
- rhodolith
- bivalves, brachiopods
- phosphatic nodules

Structures



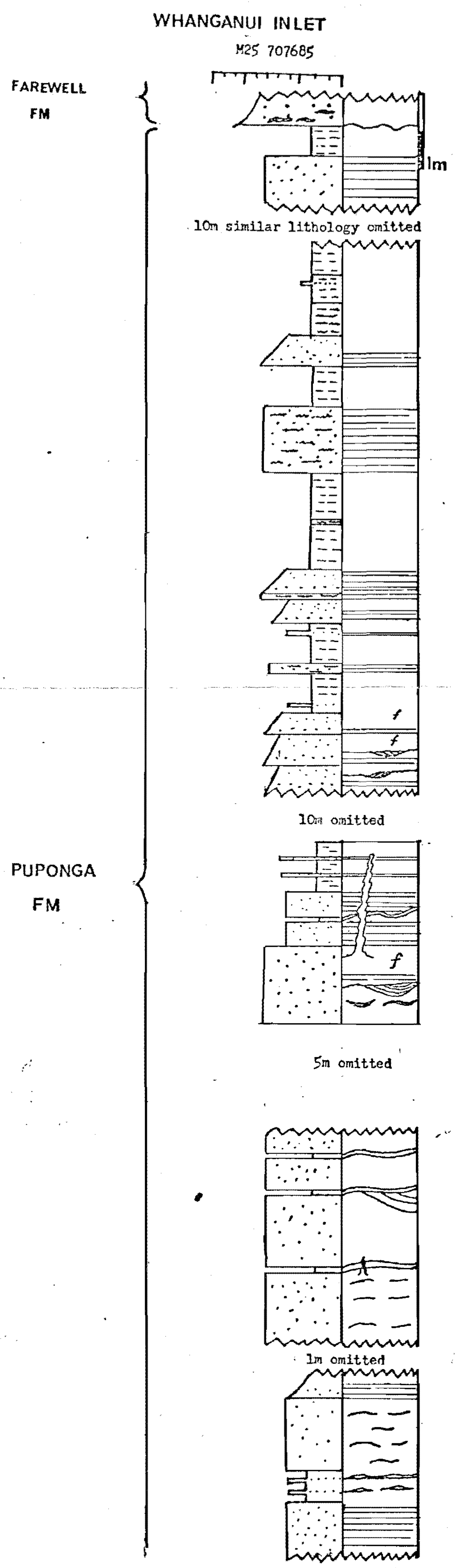
- massive
- horizontal lamination
- low angle channel-fill cross-lamination
- horizontal bedding
- channel-fill cross-stratification
- planar cross-stratification
- trough-fill cross-stratification
- crudely stratified conglomerate
- flaser bedding
- lenticular bedding
- small scale ripples
- climbing-ripples
- silt 'drapes'
- silt lense lining scour surface
- sandstone dykes
- liquefaction features
- load cast
- convolute lamination
- massive, biotubate with remnant lamination
- sand infilled tubular burrows and burrows resembling Arthrophycus
- burrows resembling Planolites
- Ophiomorpha burrows
- in-situ plant st[illegible]

PUPONGA FM



WHANGANUI INLET
M25 707685
FAREWELL
FM
1m
10m similar lithology omitted
10m omitted
PUPONGA
FM
5m omitted
1m omitted

PUPONGA FM


WHANGANUI INLET
M25 707685
FAREWELL
FM
1m
10m similar lithology omitted
10m omitted
PUPONGA
FM
5m omitted
1m omitted